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24 July 1996

Mesospheric Response to Impacting Relativistic Electrons

Final Report

Period: 21 July 1995 through 20 July 1996

Contract P.O. S-57779-F

D.L. Chenette
Lead Investigator

Space Sciences Laboratory
Lockheed-Martin Palo Alto Research Laboratories
LMMS/ATC O/91-20 B/252
Palo Alto, CA 94304-1191

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13. ABSTRACT (Maximum 200 words)
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Introduction

The Space Sciences Laboratory (O/H1-11) of the Lockheed Martin Missiles and Space Company's Advanced Technology Center (LMMS/ATC) is supporting Dr. Richard Goldberg of the NASA Goddard Space Flight Center in a scientific investigation of the effects of relativistic electron precipitation on the chemical composition and dynamics of the mesosphere. This is the final progress report of the 1-year effort performed at LMMS in this collaboration.

Results

During the past year most of the resources provided by the purchase order were used to support the efforts of Mr. Edward E. Gaines and Spacerad in the reduction and analysis of the electron data from the PEM/HEPS instrument aboard UARS. As a result, the bulk of this report consists of Mr. Gaines's reports of his progress and results. These are attached as Appendix A, B, and C.

The results described in the Appendix have been provided informally to Dr. Goldberg and discussed with him is face-to-face meetings at Lockheed Martin. In addition, daily maps of precipitating electron intensity have been produced for the May 1992 period of highest precipitating electron intensity. These also have been provided directly to Dr. Goldberg. Copies are attached.

Summary

Based on plots of the daily electron intensity, the largest events observed aboard UARS for the period from October 1991 through mid-1995 were identified. Based on these results together with careful consideration of the availability of data from other UARS investigations, a prioritized list of intervals was agreed upon for more detailed investigation. The following intervals were selected, shown here in priority order:

11 - 21 May 1992
10 - 20 October 1991
24 November - 21 December 1991
4 - 8 November 1991
and 6 April - 3 May 1993

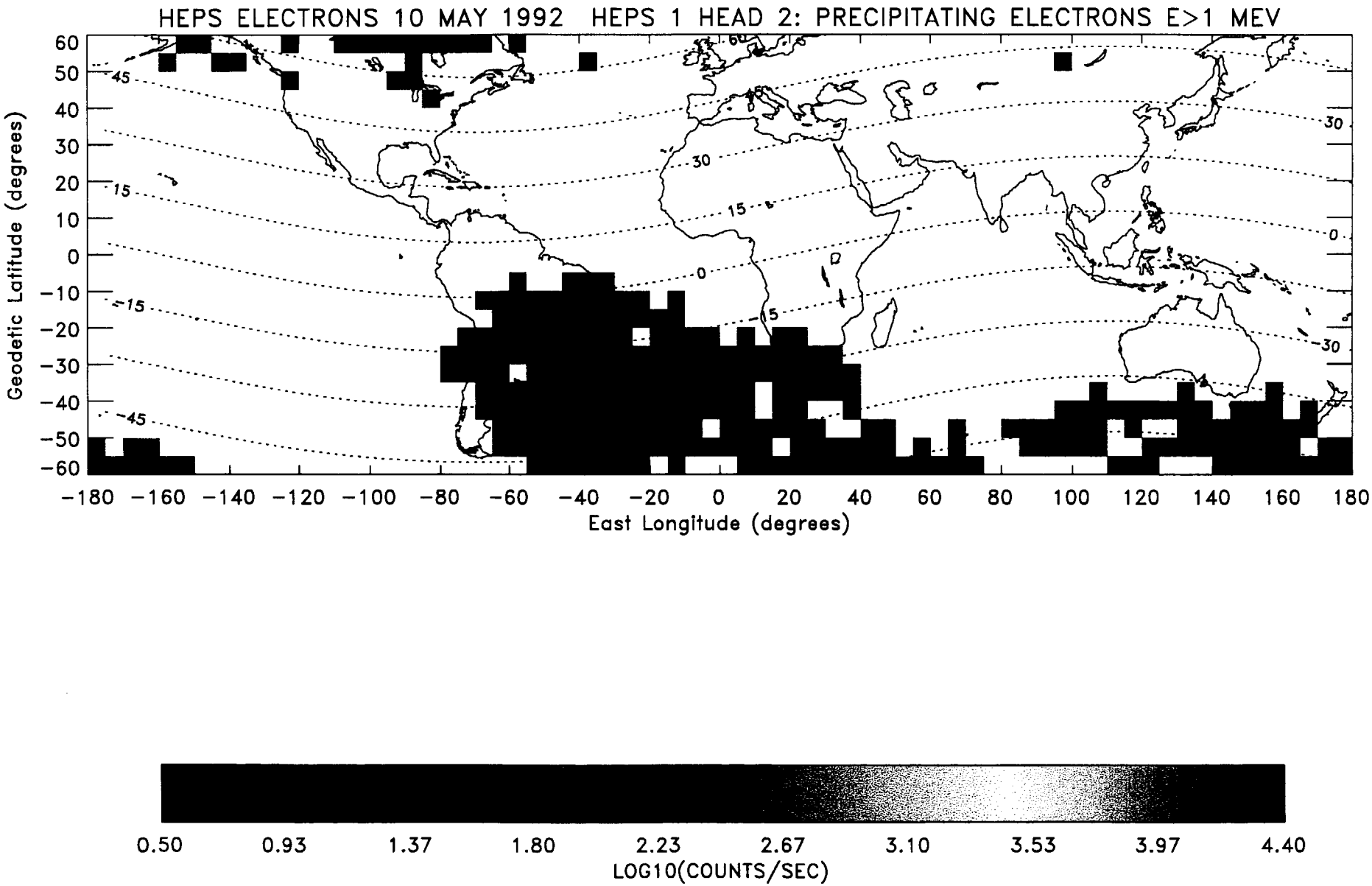
The 11-21 May 1992 interval is the highest priority and in discussions with Dr. Goldberg we agreed to give it the most attention in our analysis.

Relativistic electron energy spectra from the HEPS instrument were calculated in detail for each day of the May 1992 period, and in summary form for the November 1991 and December 1991 periods. Indications of the temporal and spatial variations of the precipitating electron intensity were provided with samples obtained at different places and times within each event period. The precipitated electron flux intensities and energy spectra were also used to calculate altitude profiles of ion production rates throughout the mesosphere. During the most intense parts of the May 1992 period, between the 12th and 14th of May, ion production rates exceeded 100 ions cm^{-3} s^{-1} at altitudes between 55 and 80 km.

Daily maps of the precipitating electron flux intensity were produced for the May 1992 period. They showed that the most intense precipitation observed by UARS was in the southern hemisphere, south of Africa and between 45° and 60° south magnetic latitude. This localization effect is at least partially the result of the geometry of the earth's magnetic field, specifically the offset of the magnetic center towards the north Pacific region.

Conclusions and Recommendations

Based on this study we conclude that there were extended periods of significant enhancements in the ion production rate down to below 60 km altitude as a result of relativistic electron precipitation. This result is quantified in the attached reports. The major electron precipitation event of May 1992 is thoroughly analyzed. We recommend that the spatial and temporal variations in the electron precipitation be compared to variations in the composition of trace species as revealed by the UARS atmospheric composition instruments, specifically CLAES and HALOE, but possibly also including MLS. We look forward to a continuation of this collaboration for two more years to work on this aspect of the problem. Now that we have characterized the input, in this way we hope to characterize the mesospheric response of the impacting relativistic electrons.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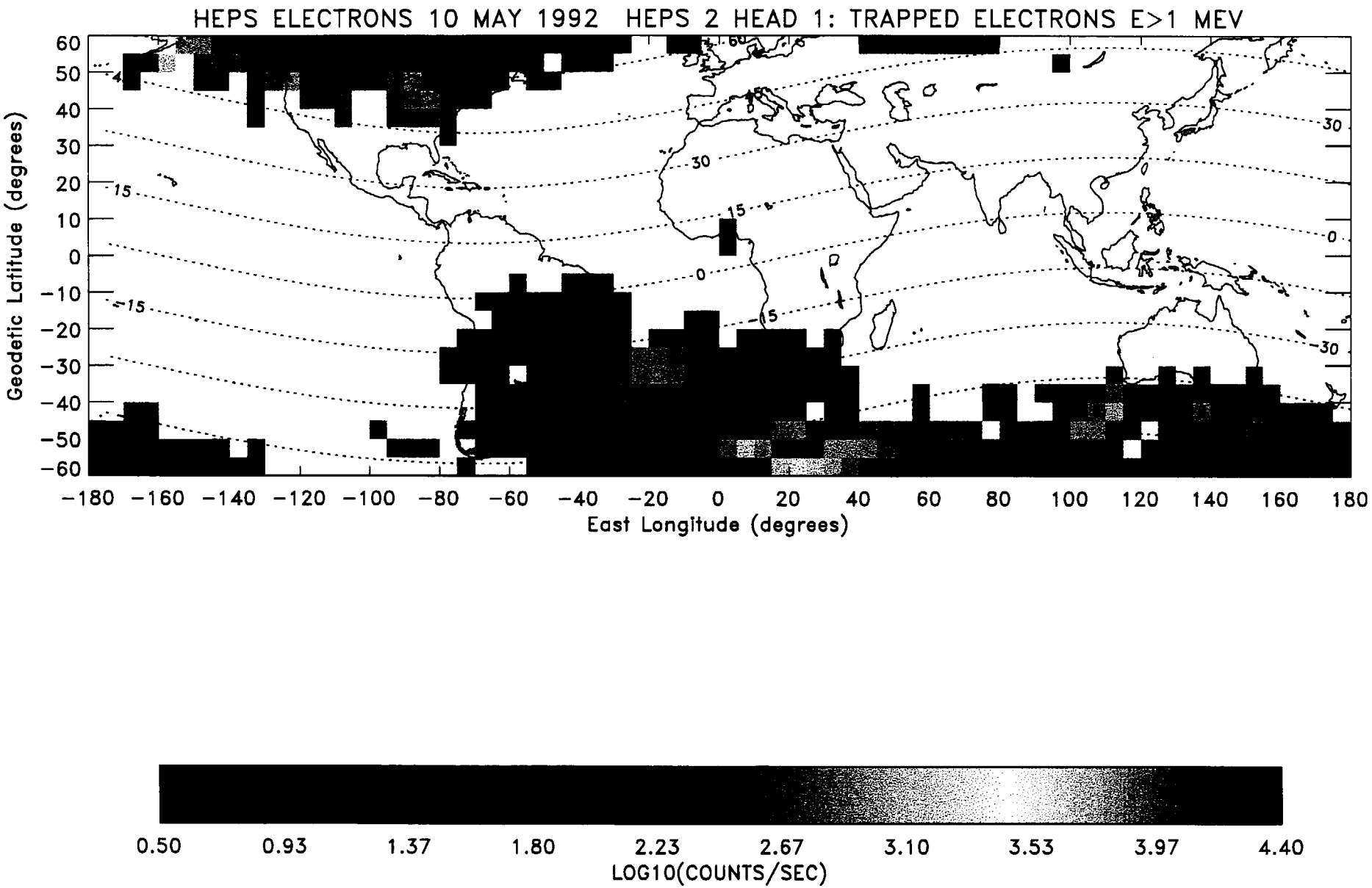
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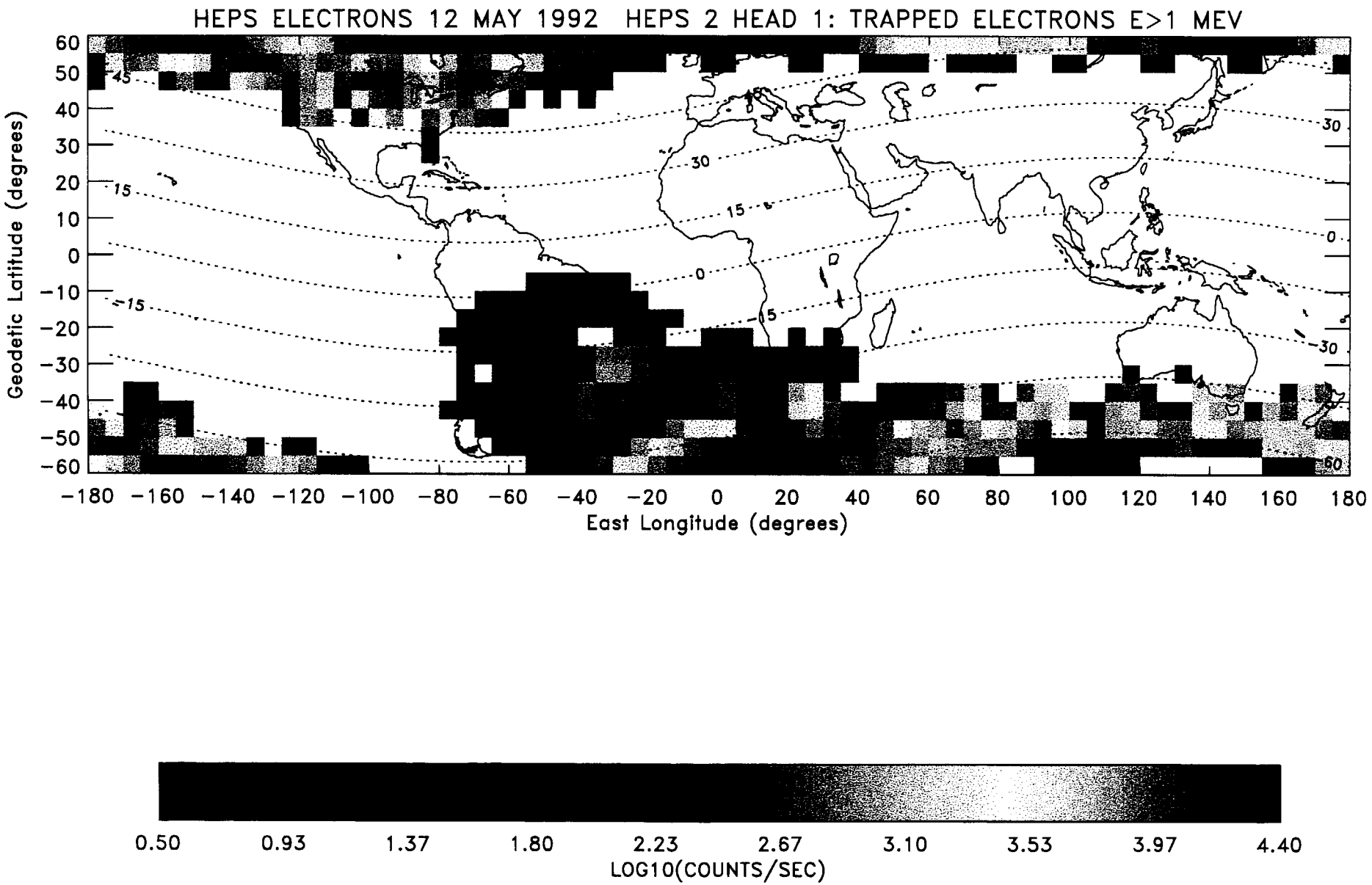
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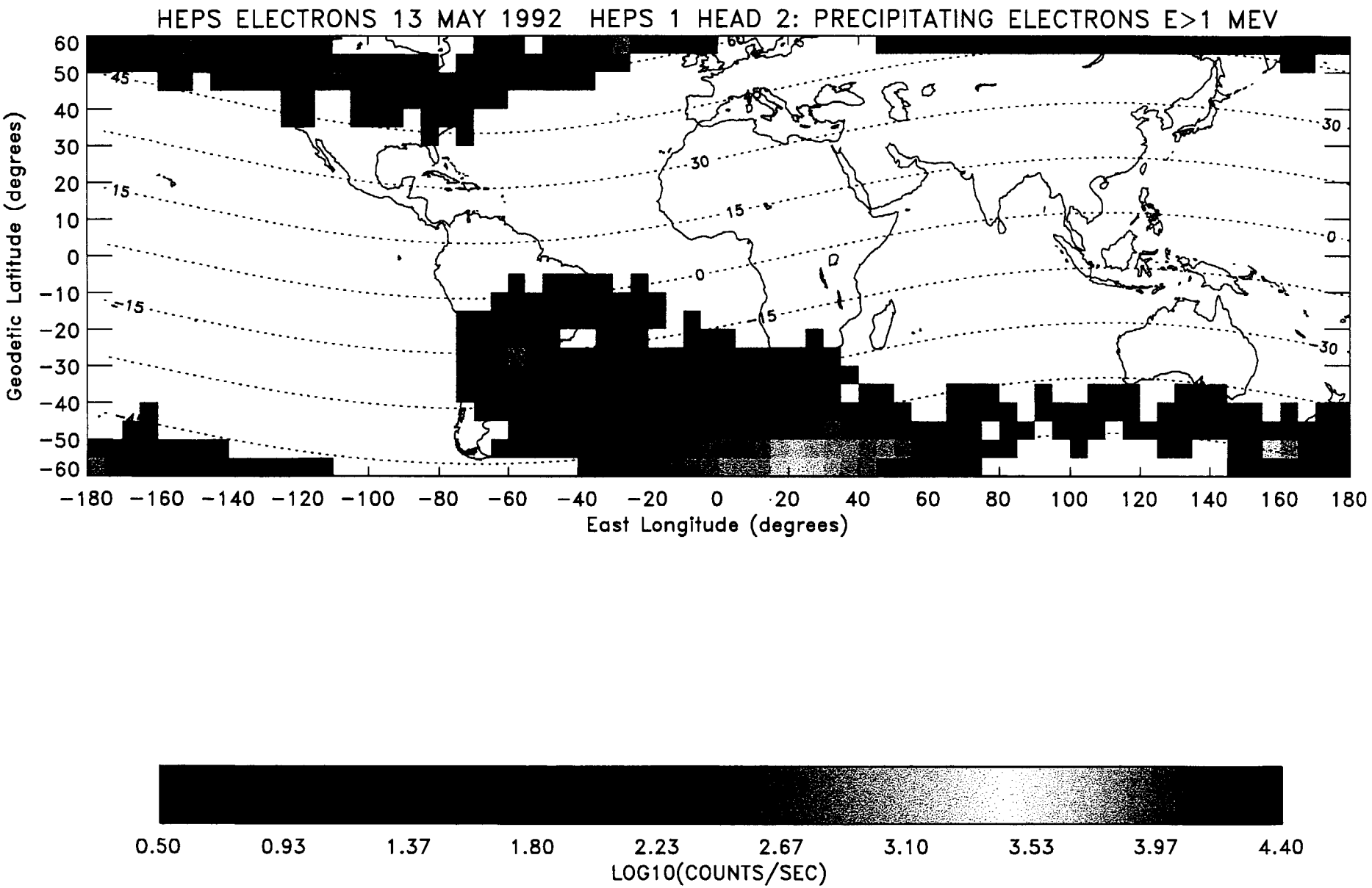
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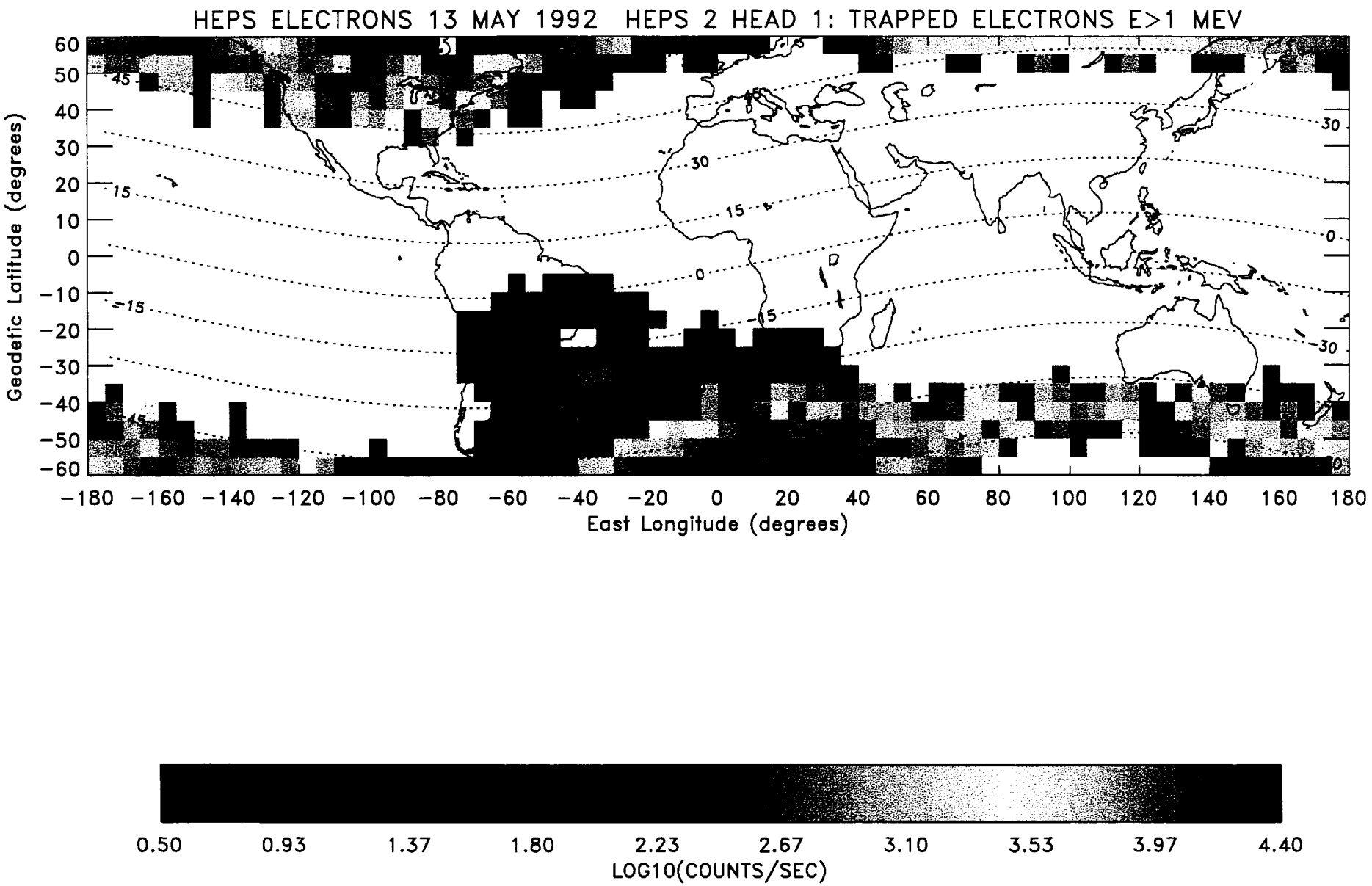
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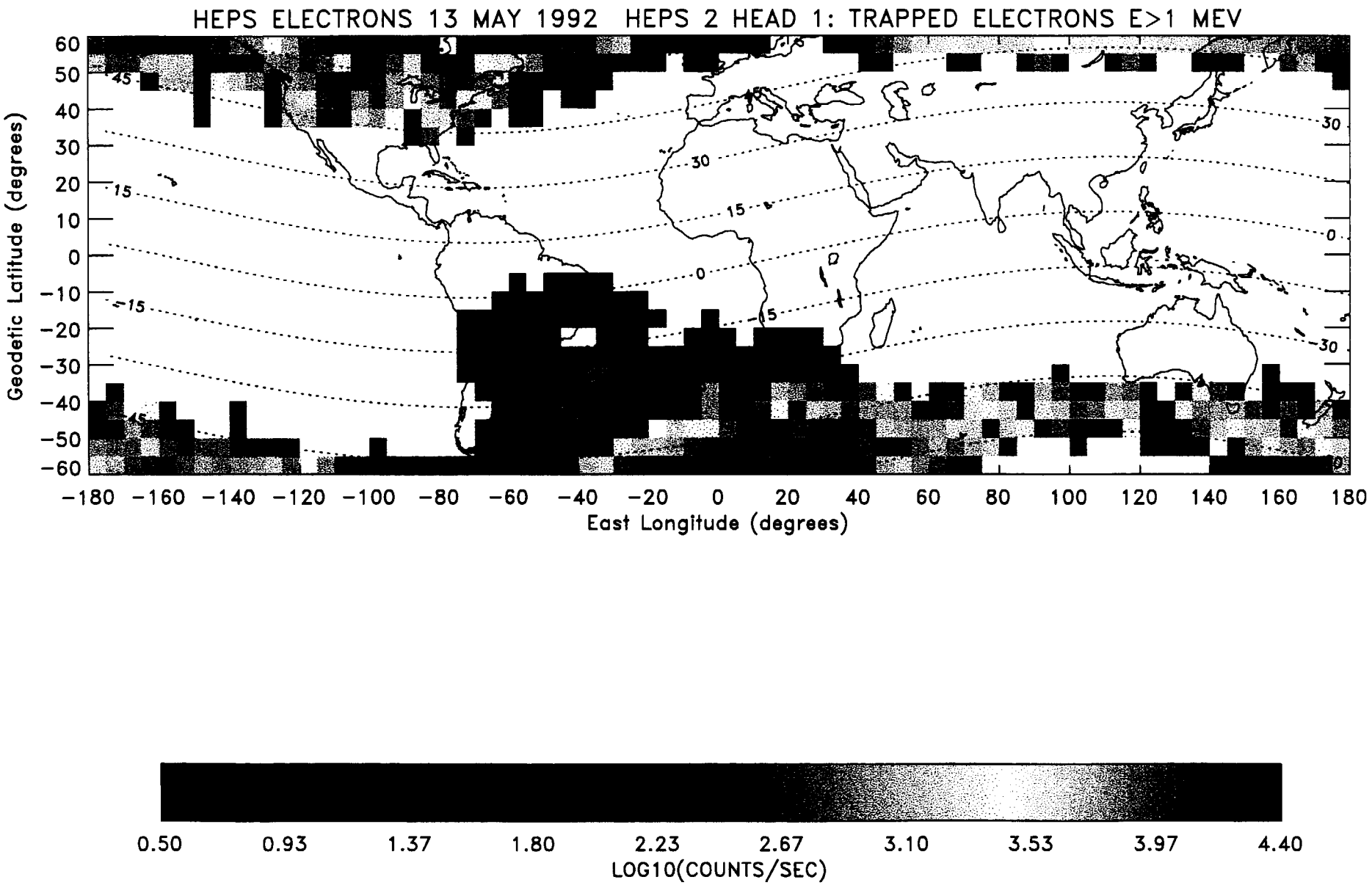
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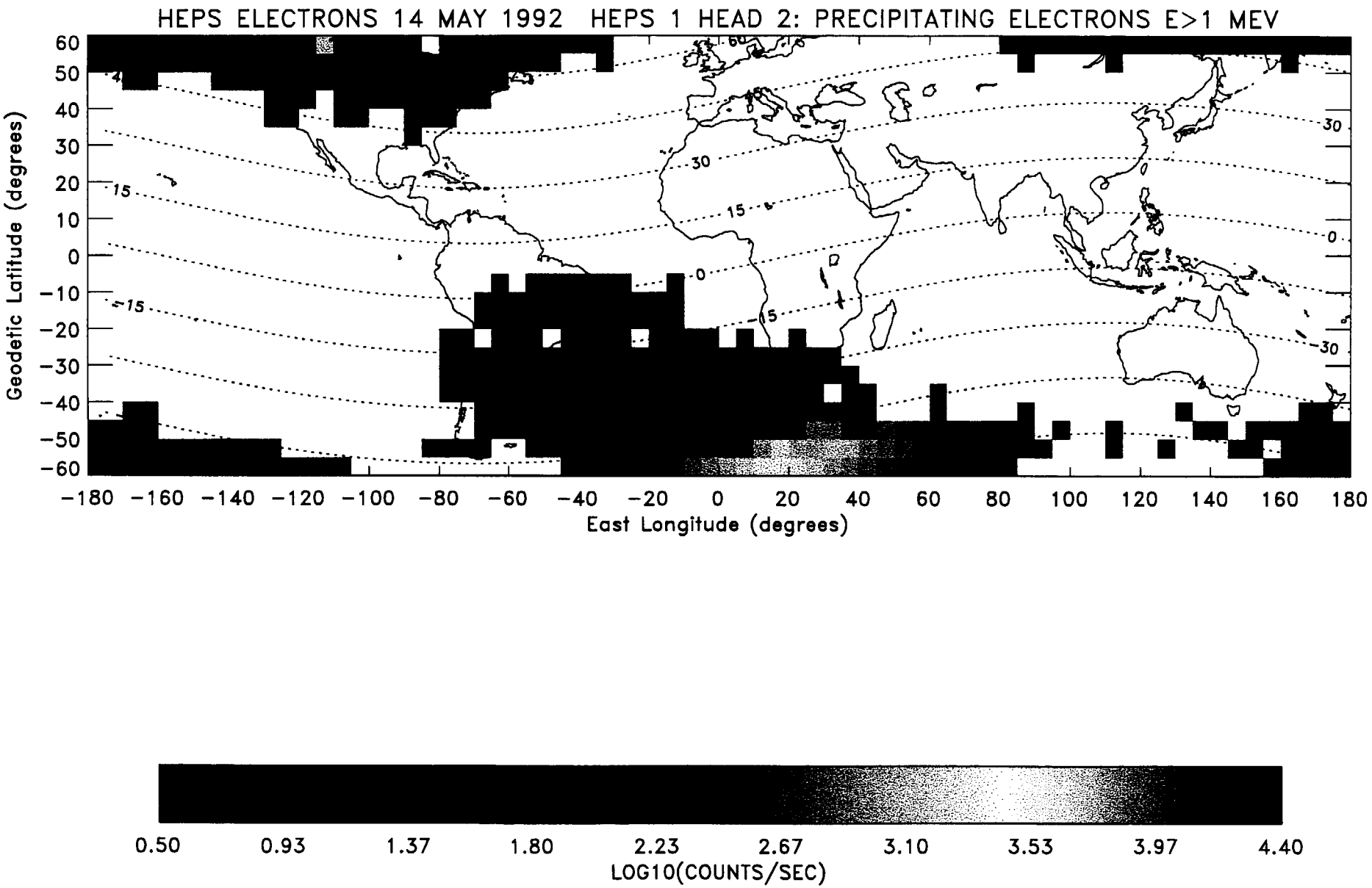
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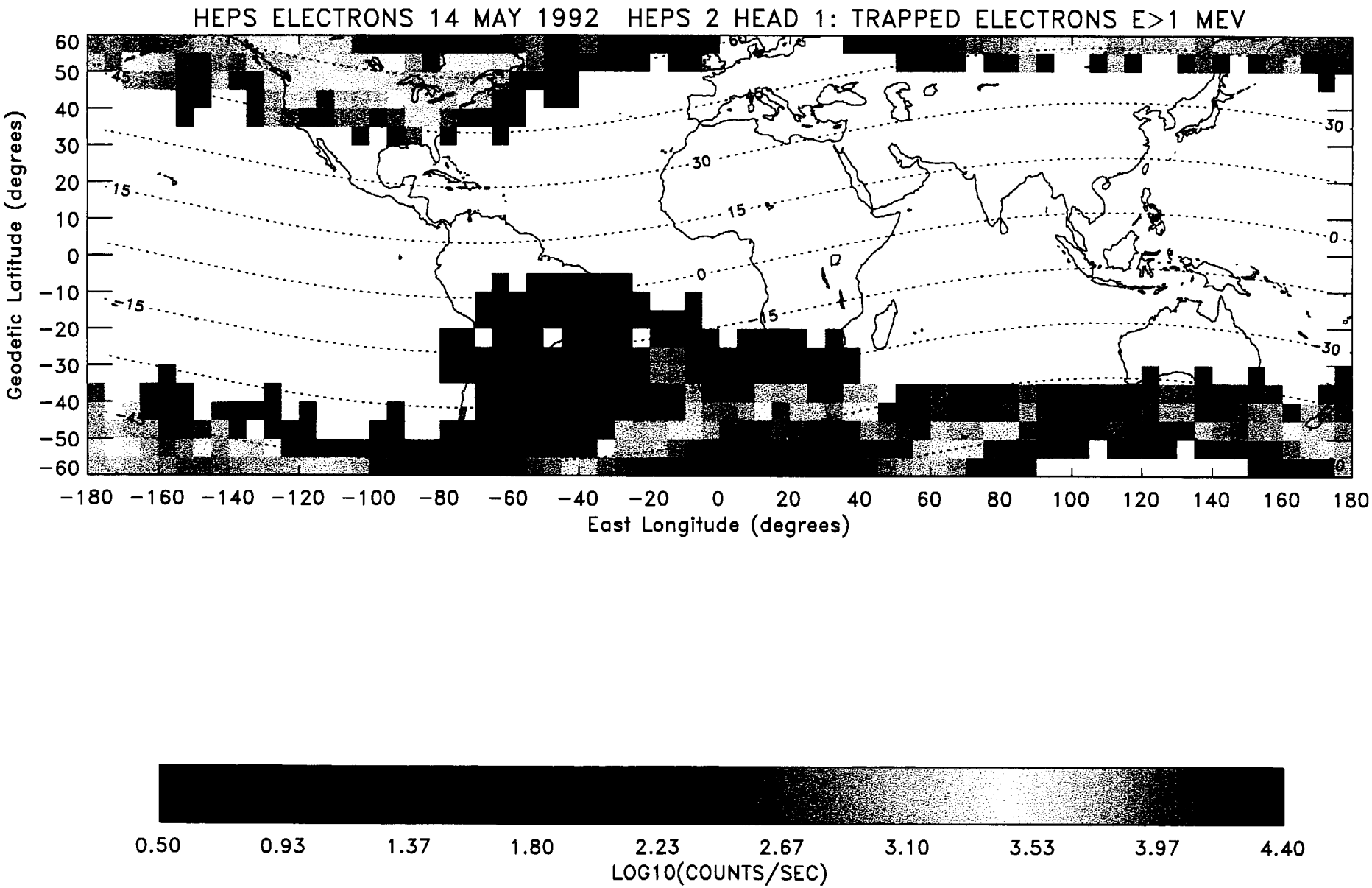
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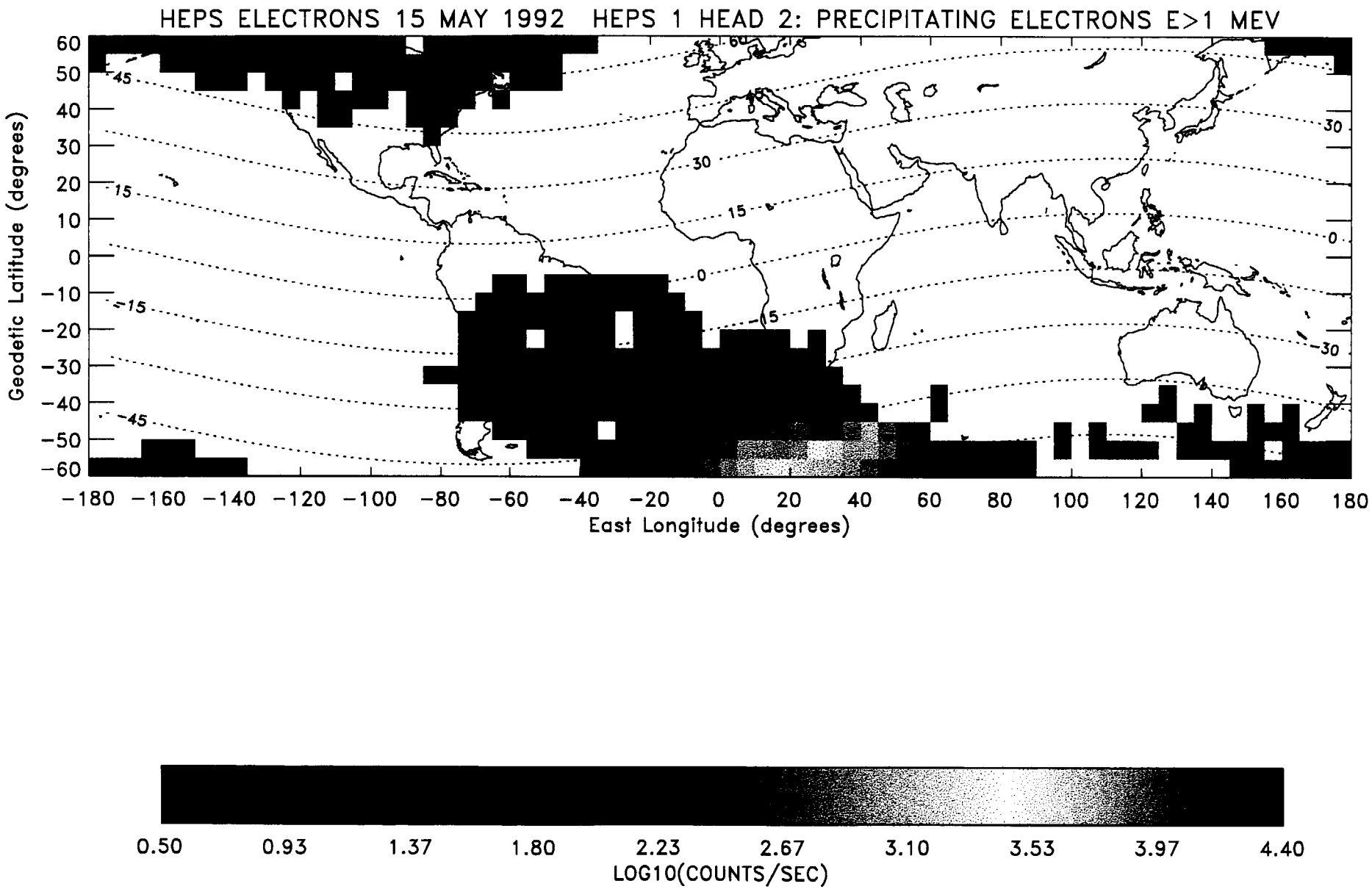
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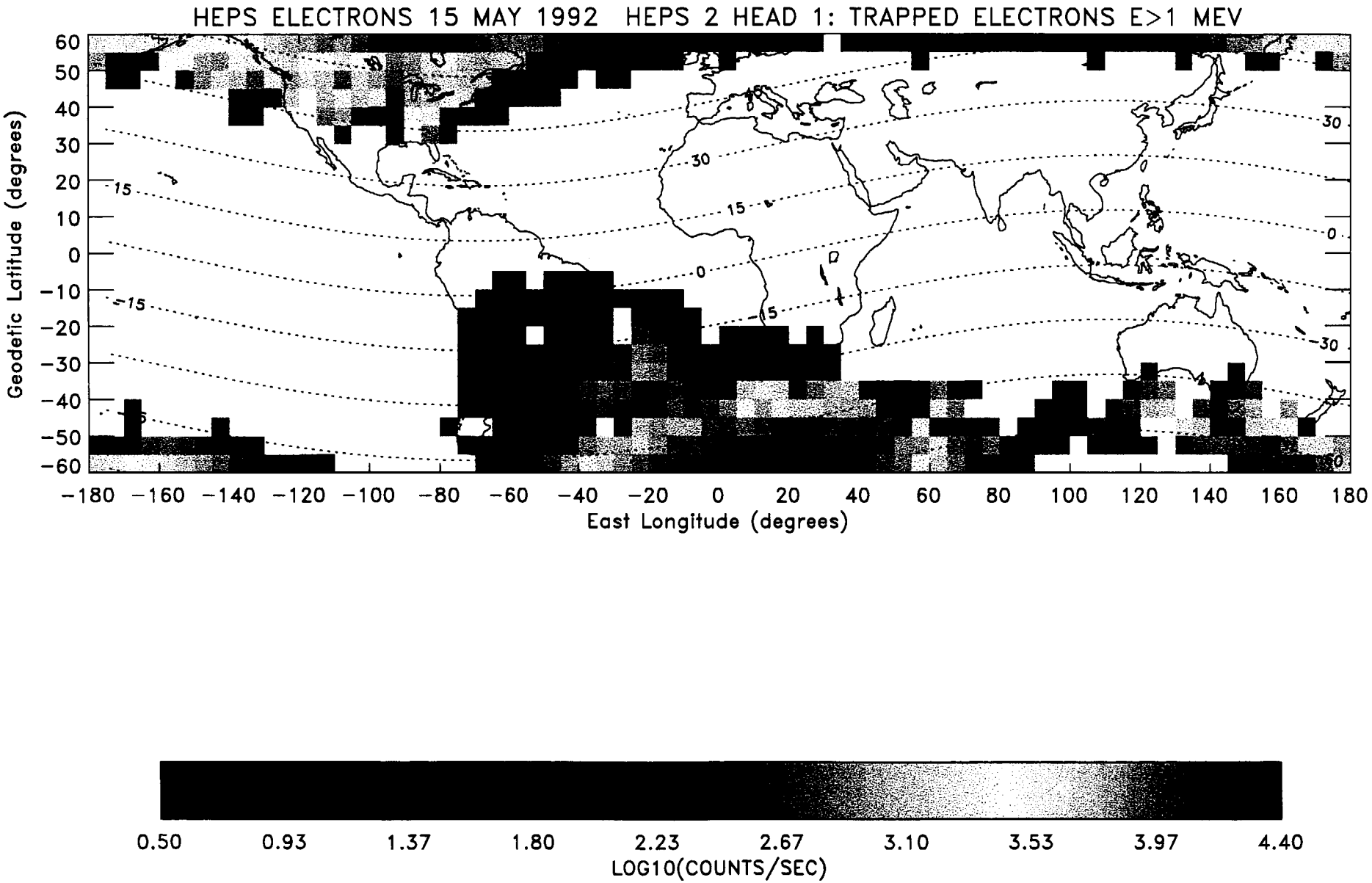
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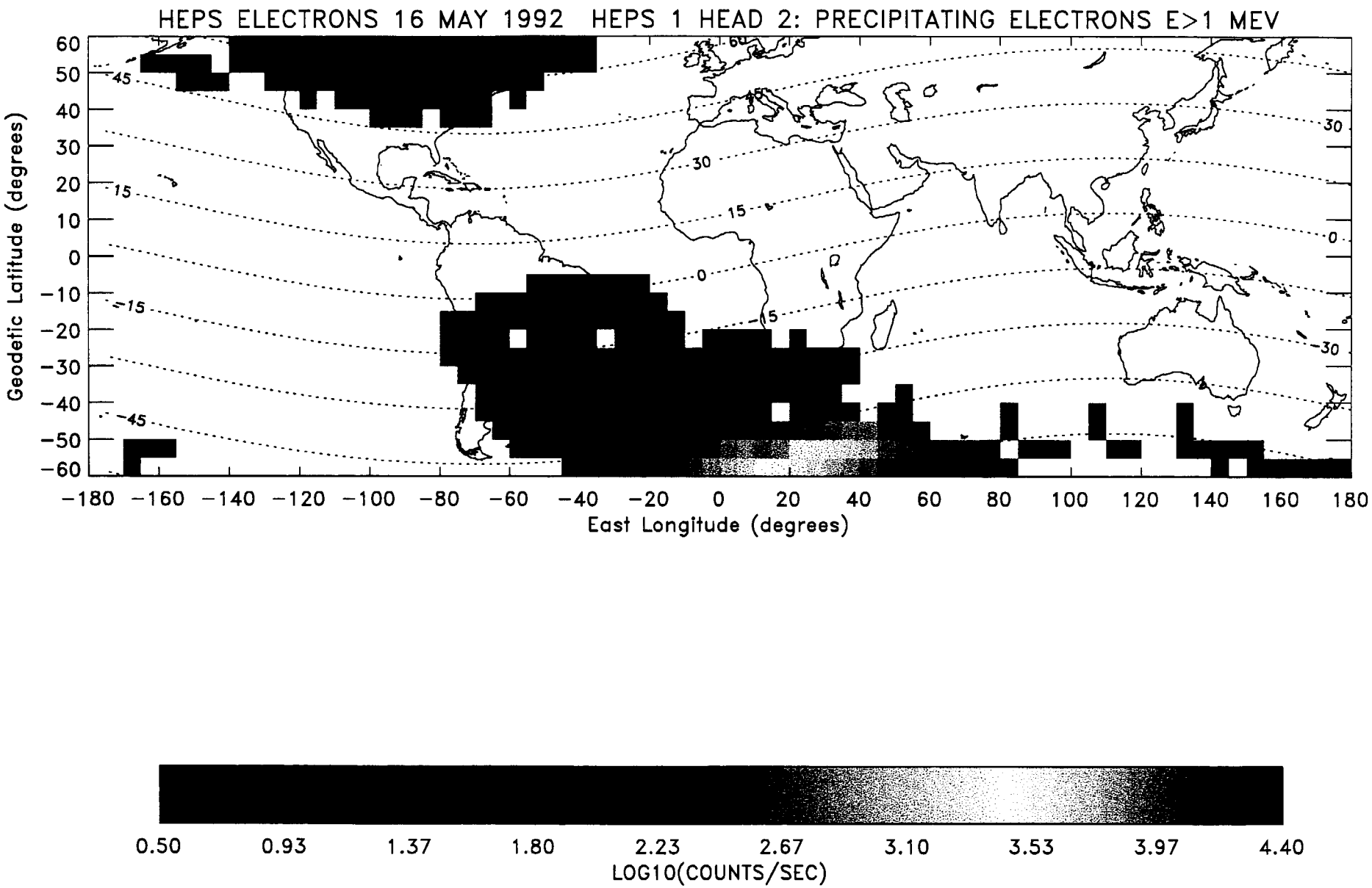
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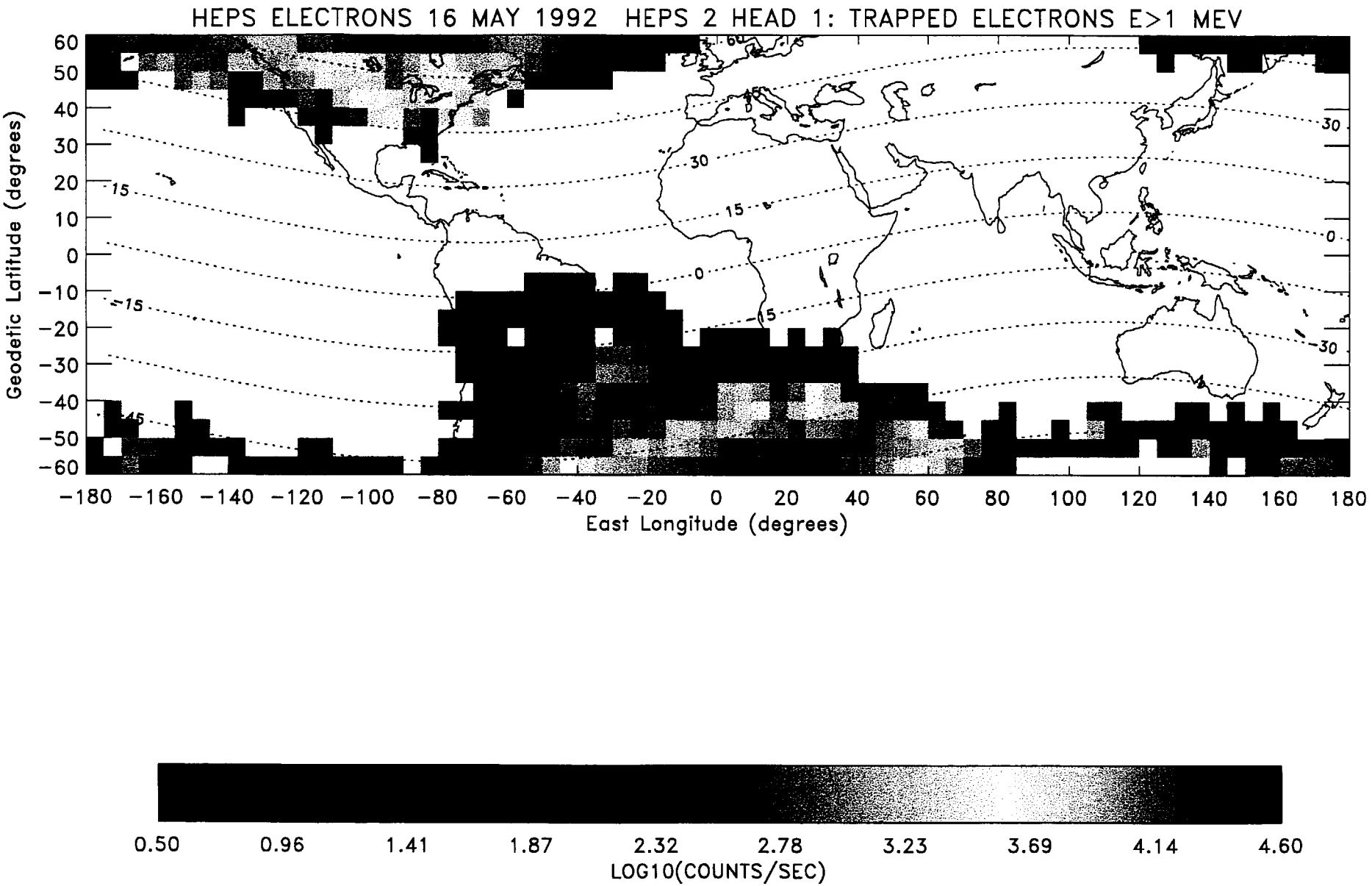
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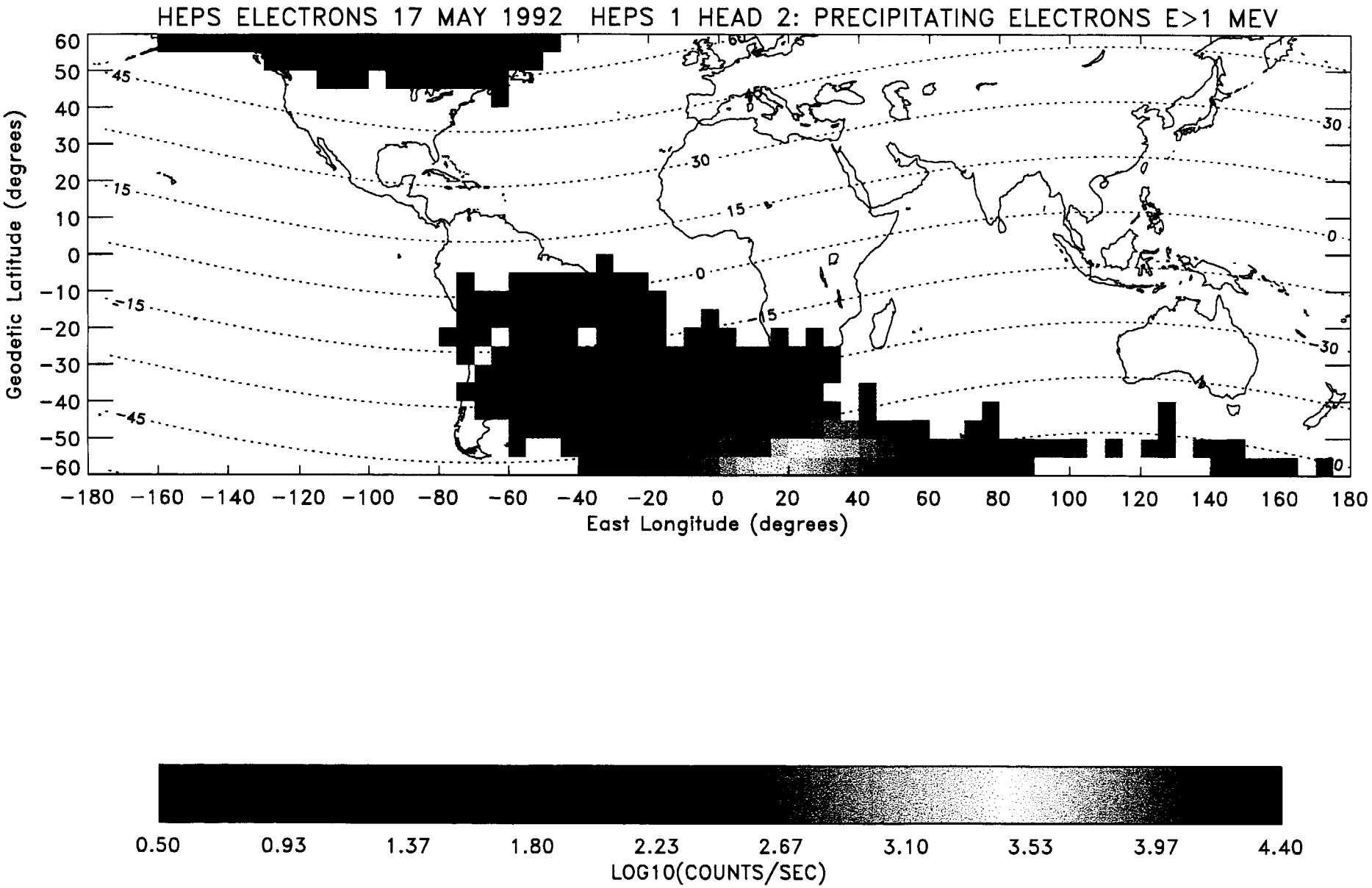
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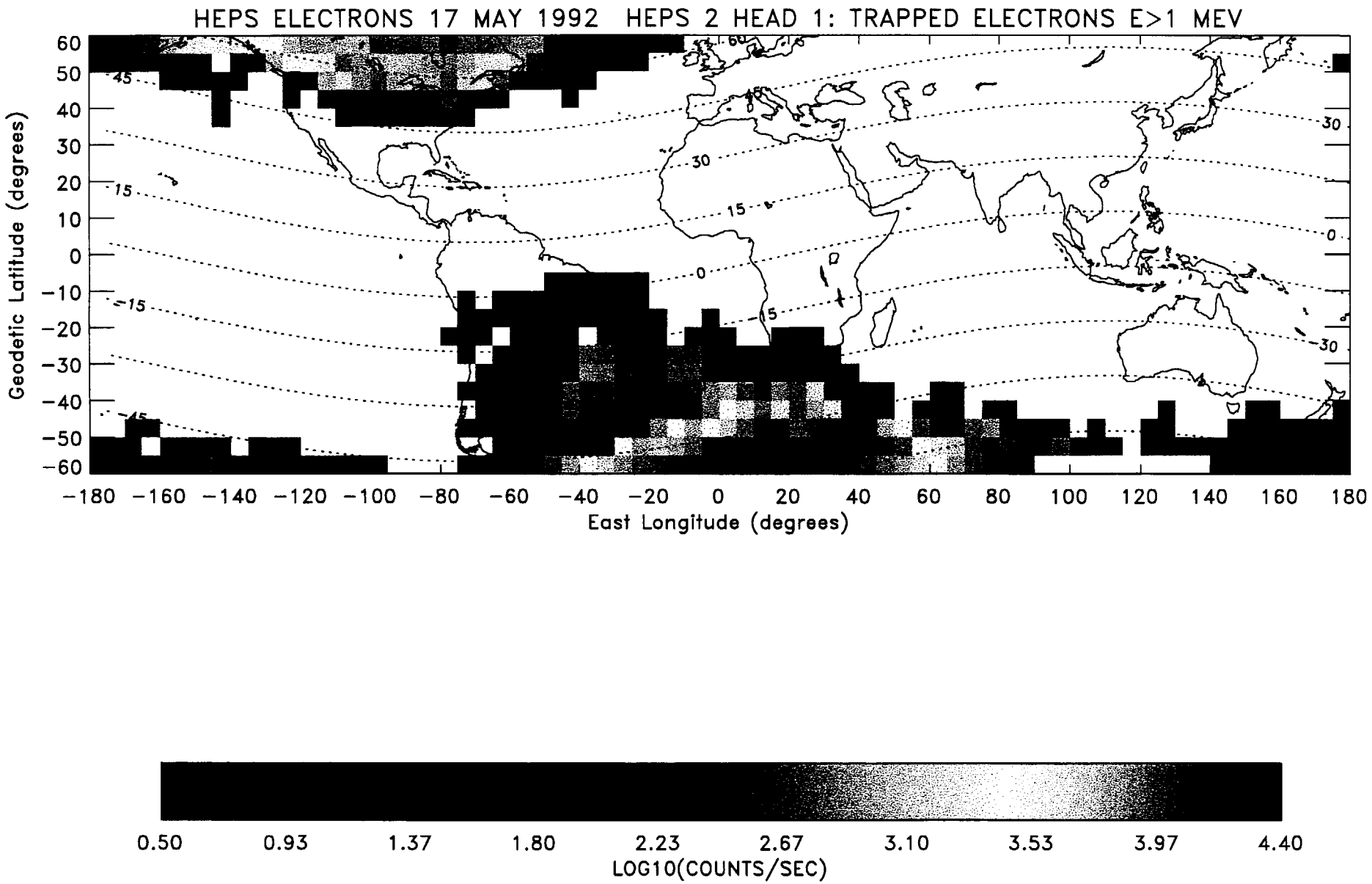
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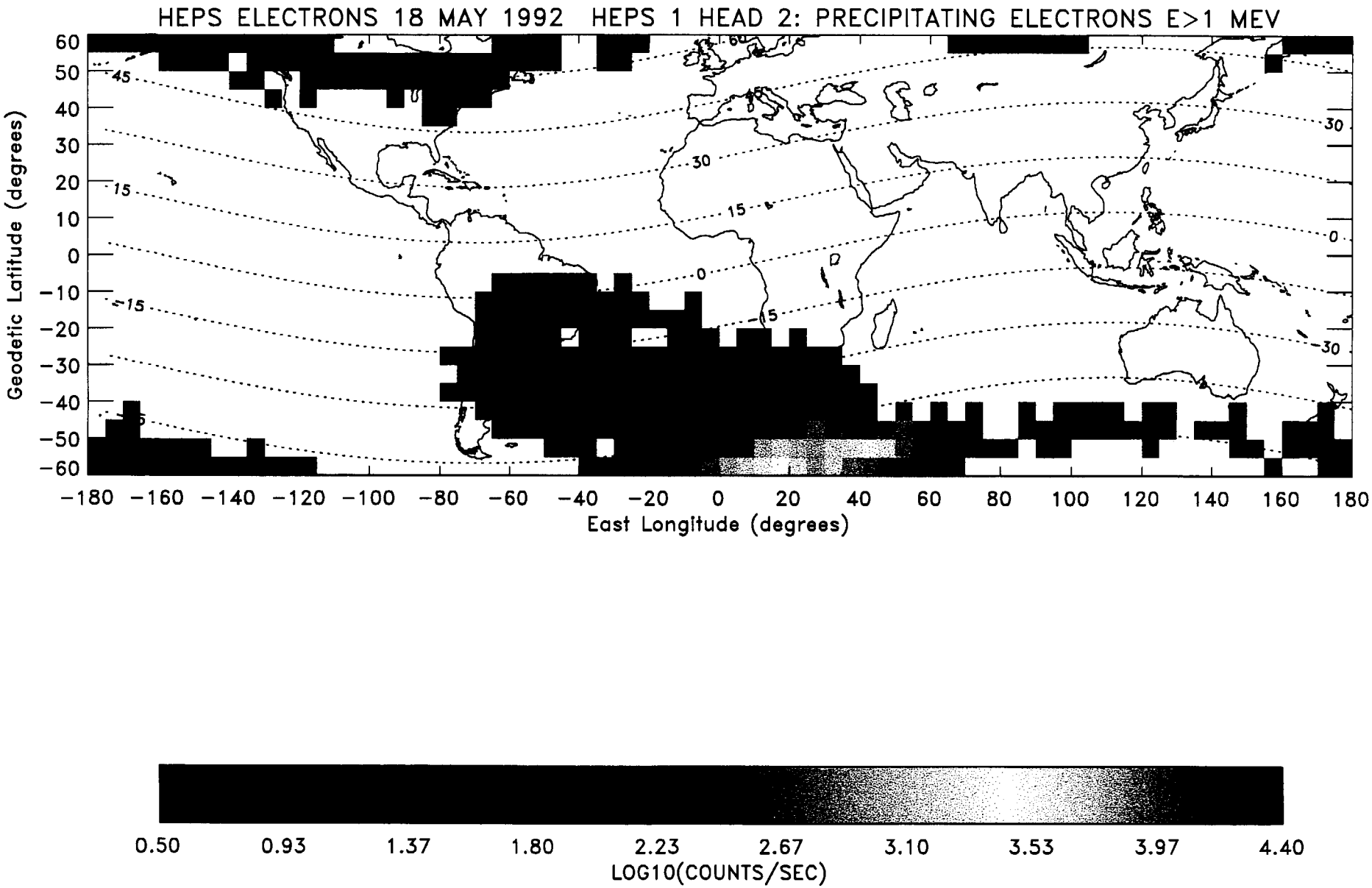
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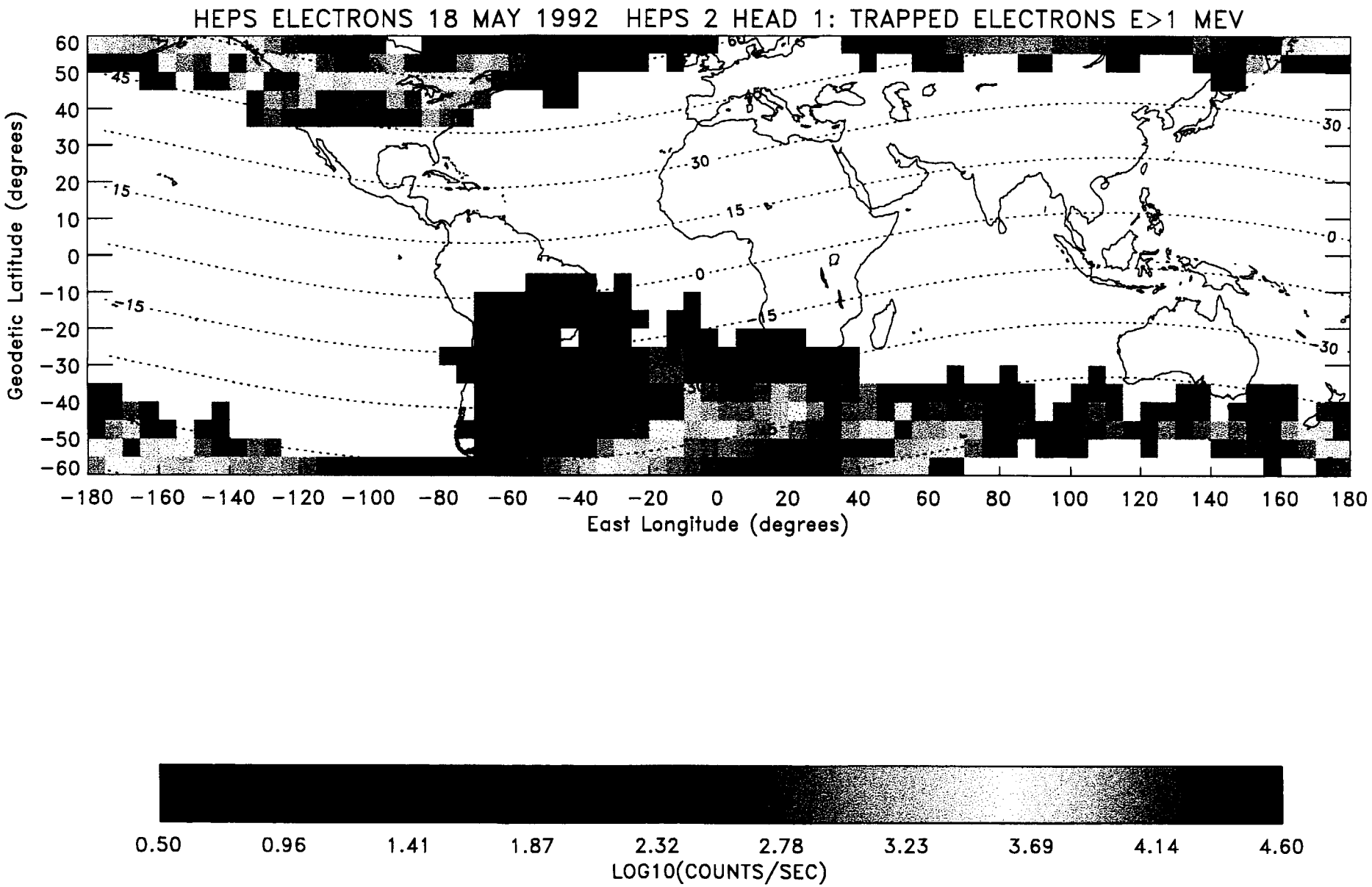
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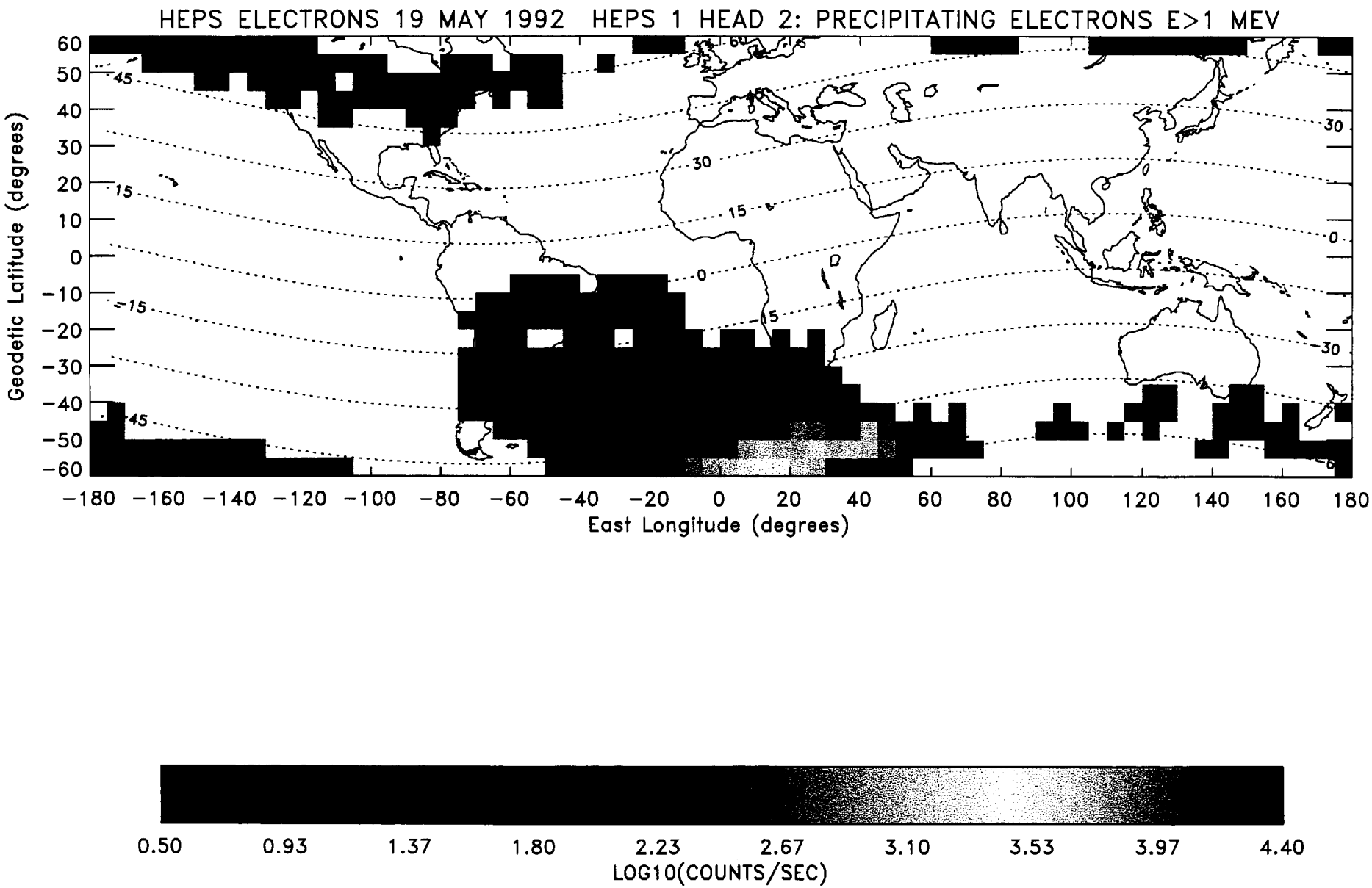
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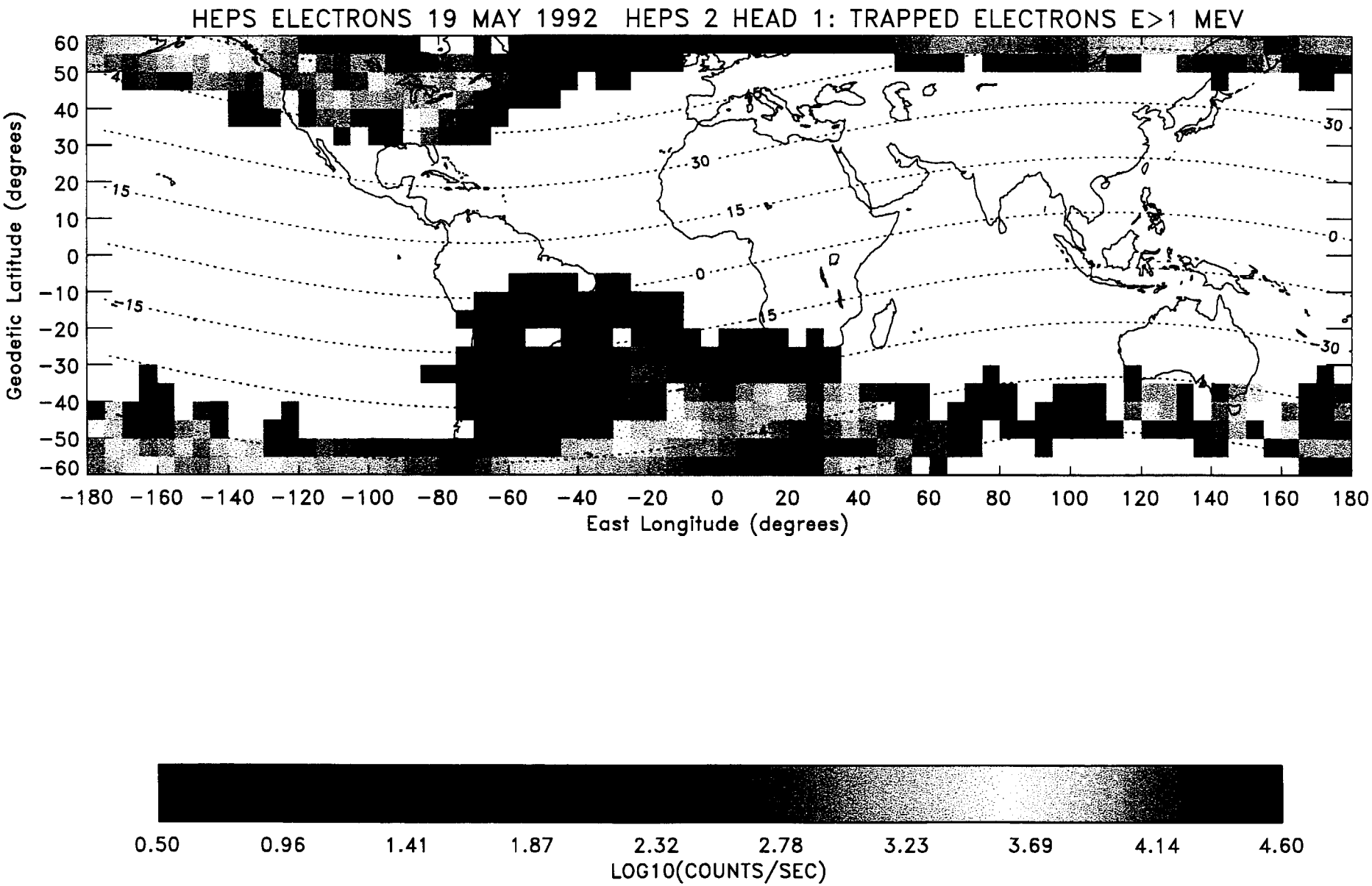
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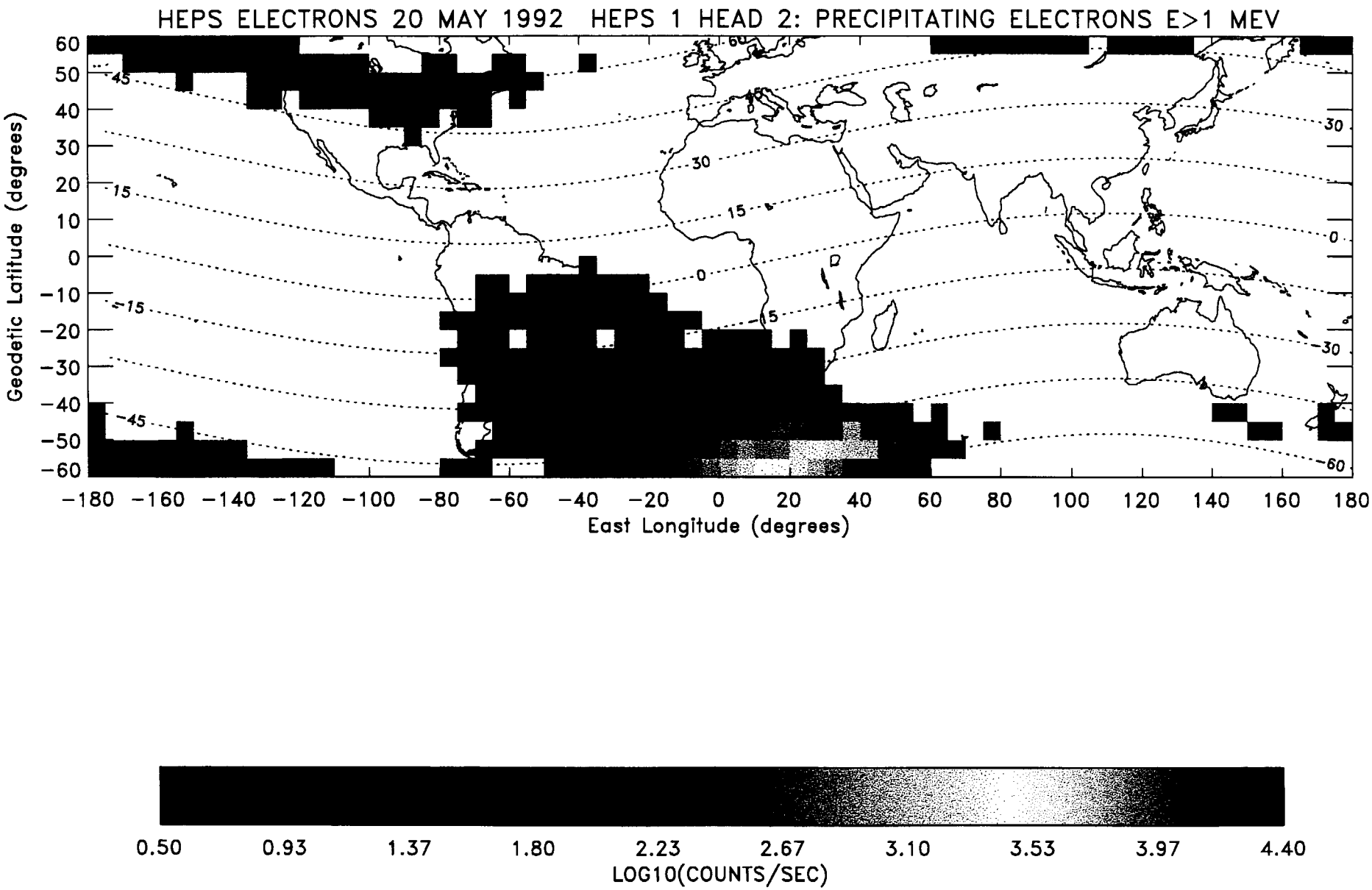
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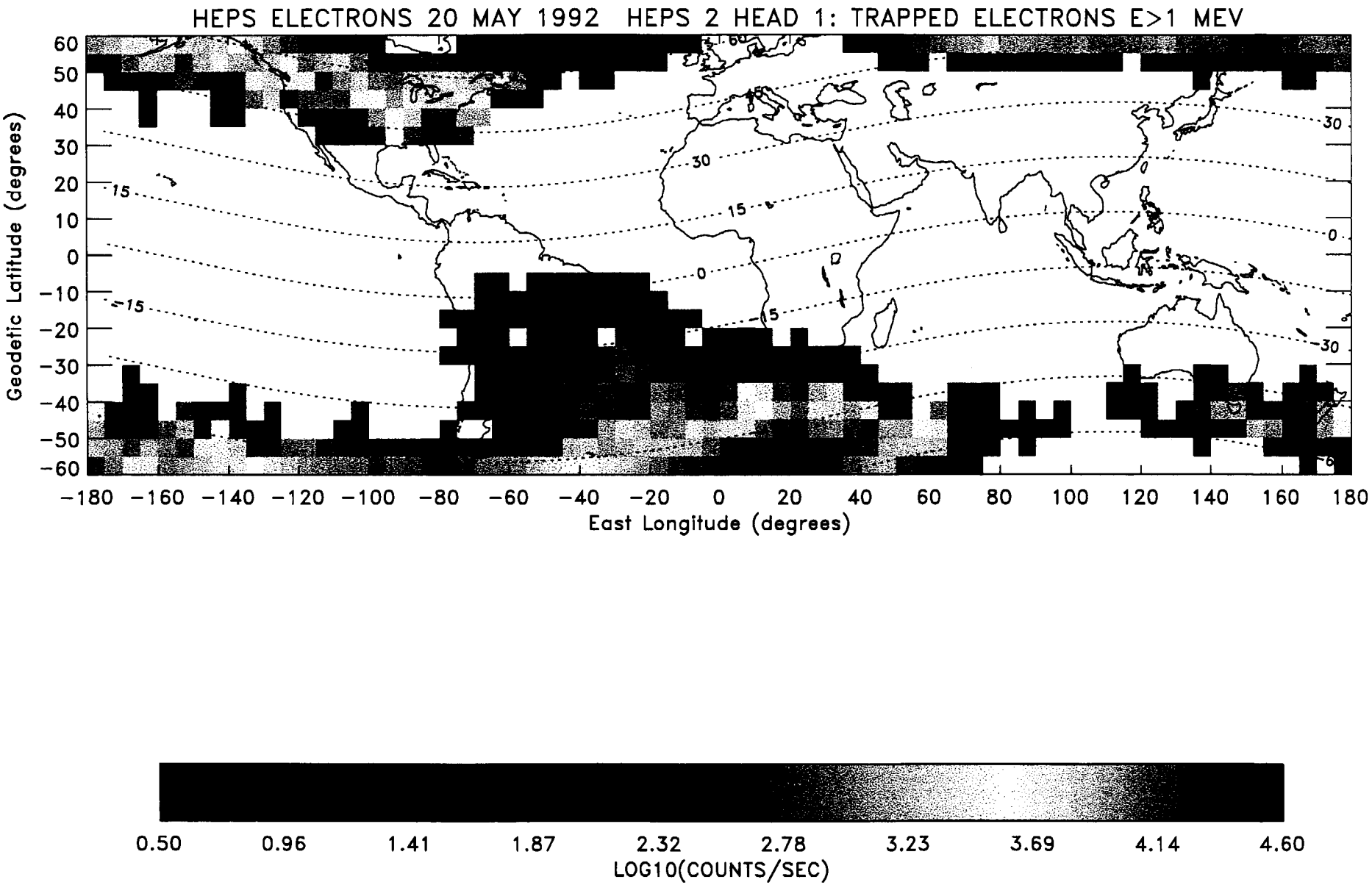
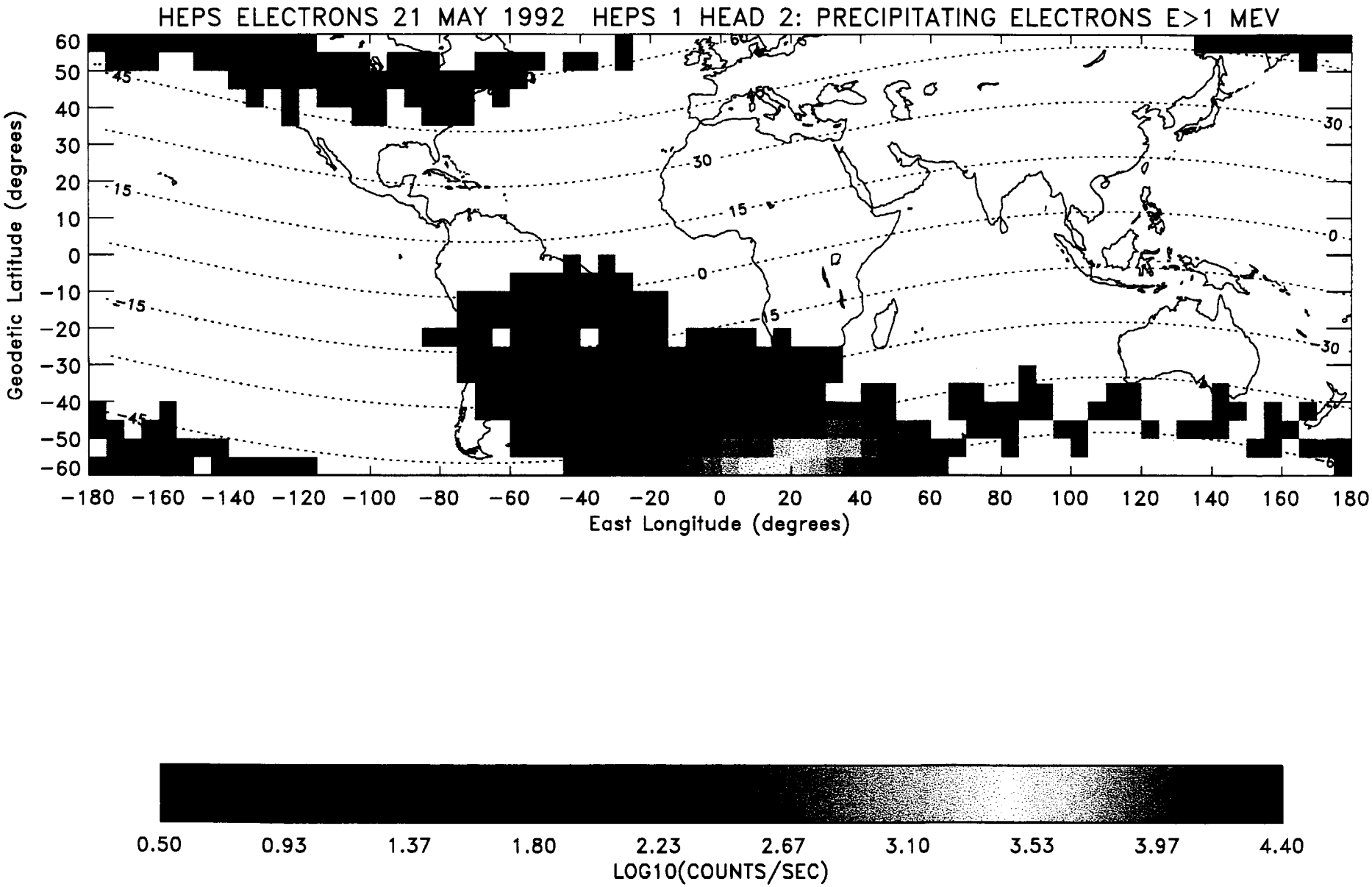
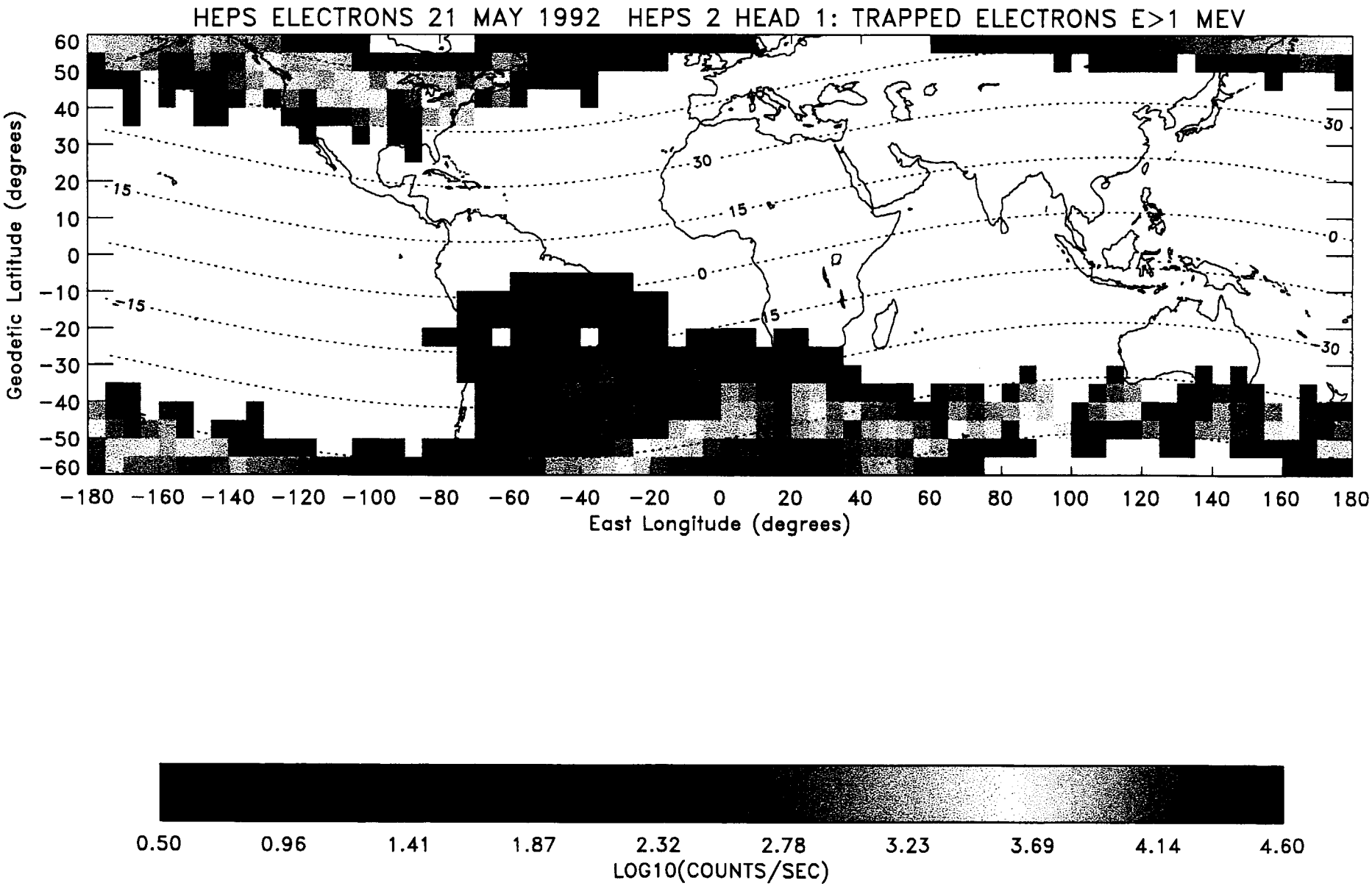
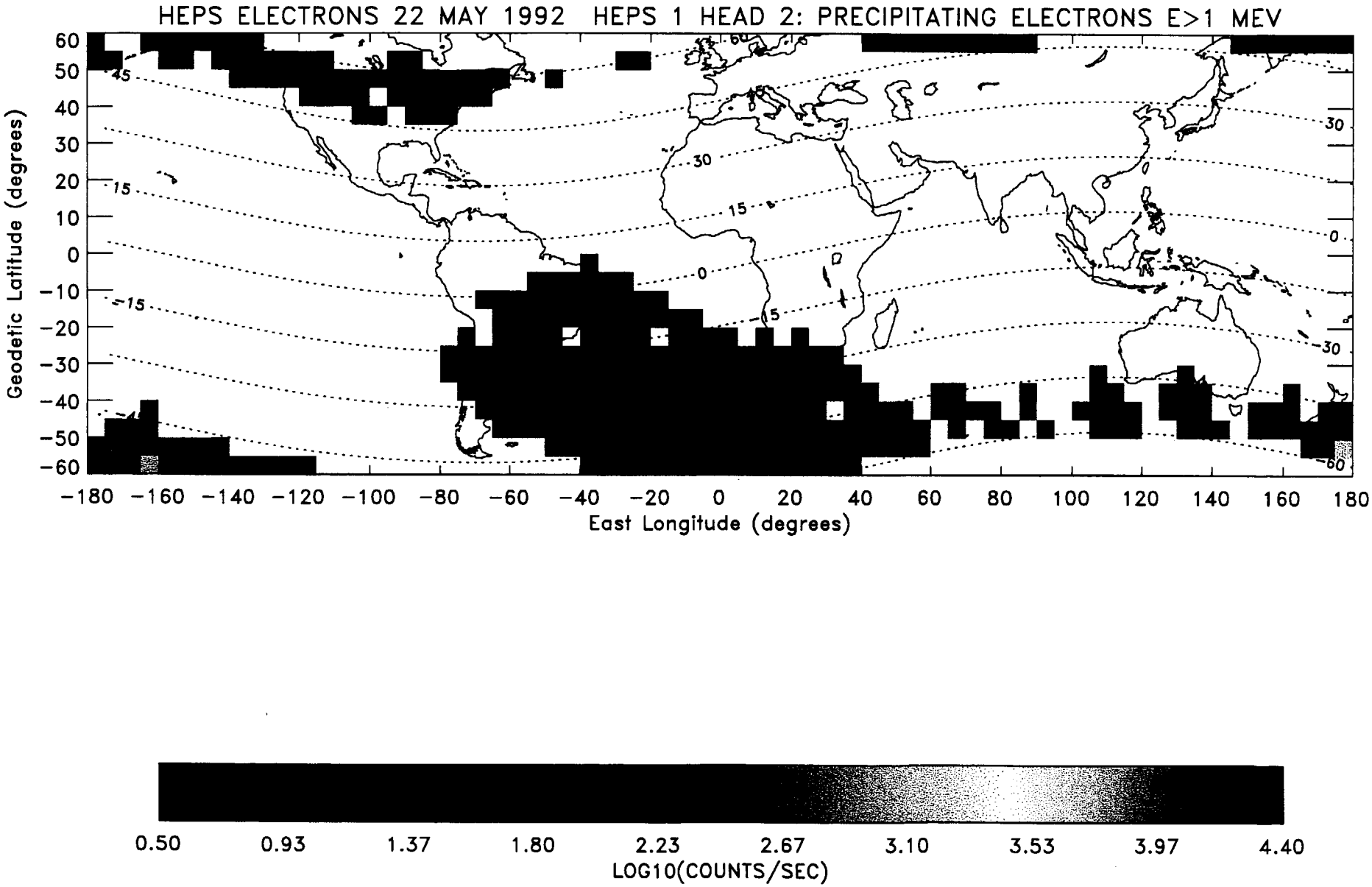
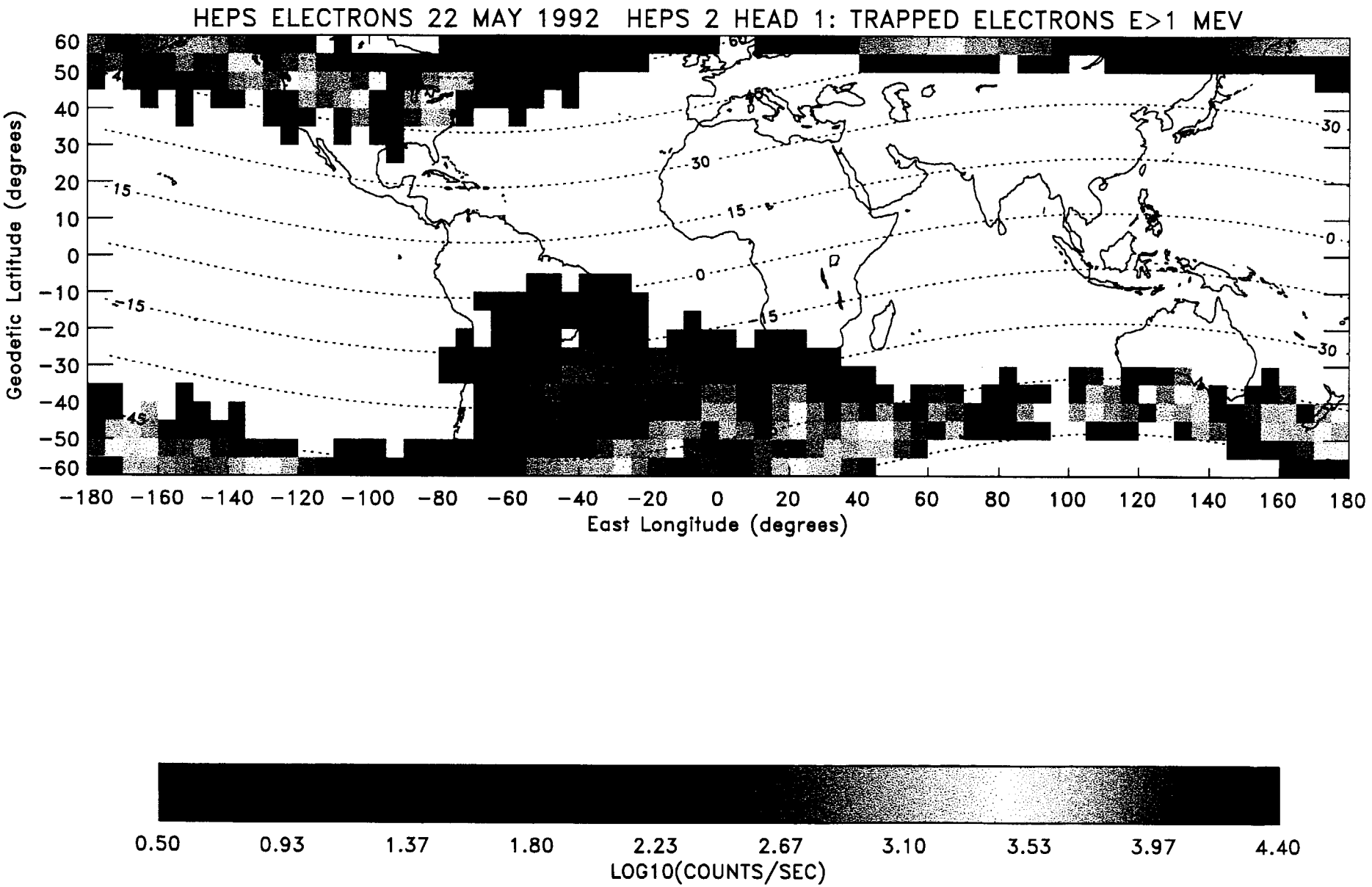

HEPS ELECTRONS 20 MAY 1992 HEPS 2 HEAD 1: TRAPPED ELECTRONS E>1 MEV
Geodetic Latitude (degrees)
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−180 −160 −140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140 160 180
East Longitude (degrees)
30
15
0
−15
0.50 0.96 1.41 1.87 2.32 2.78 3.23 3.69 4.14 4.60
LOG10(COUNTS/SEC)


HEPS ELECTRONS 21 MAY 1992 HEPS 1 HEAD 2: PRECIPITATING ELECTRONS E>1 MEV
Geodetic Latitude (degrees)
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
45
15
30
15
0
−15
−15
−45
30
0
−30
−180 −160 −140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140 160 180
East Longitude (degrees)
0.50 0.93 1.37 1.80 2.23 2.67 3.10 3.53 3.97 4.40
LOG10(COUNTS/SEC)


HEPS ELECTRONS 21 MAY 1992 HEPS 2 HEAD 1: TRAPPED ELECTRONS E>1 MEV
Geodetic Latitude (degrees)
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
30
15
0
−15
−180 −160 −140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140 160 180
East Longitude (degrees)
0.50 0.96 1.41 1.87 2.32 2.78 3.23 3.69 4.14 4.60
LOG10(COUNTS/SEC)


HEPS ELECTRONS 22 MAY 1992 HEPS 1 HEAD 2: PRECIPITATING ELECTRONS E>1 MEV
Geodetic Latitude (degrees)
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
45
30
15
0
−15
−30
−60
−180 −160 −140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140 160 180
East Longitude (degrees)
0.50 0.93 1.37 1.80 2.23 2.67 3.10 3.53 3.97 4.40
LOG10(COUNTS/SEC)


HEPS ELECTRONS 22 MAY 1992 HEPS 2 HEAD 1: TRAPPED ELECTRONS E>1 MEV
Geodetic Latitude (degrees)
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−180 −160 −140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140 160 180
East Longitude (degrees)
60
45
30
15
0
−15
0.50 0.93 1.37 1.80 2.23 2.67 3.10 3.53 3.97 4.40
LOG10(COUNTS/SEC)

Appendix A

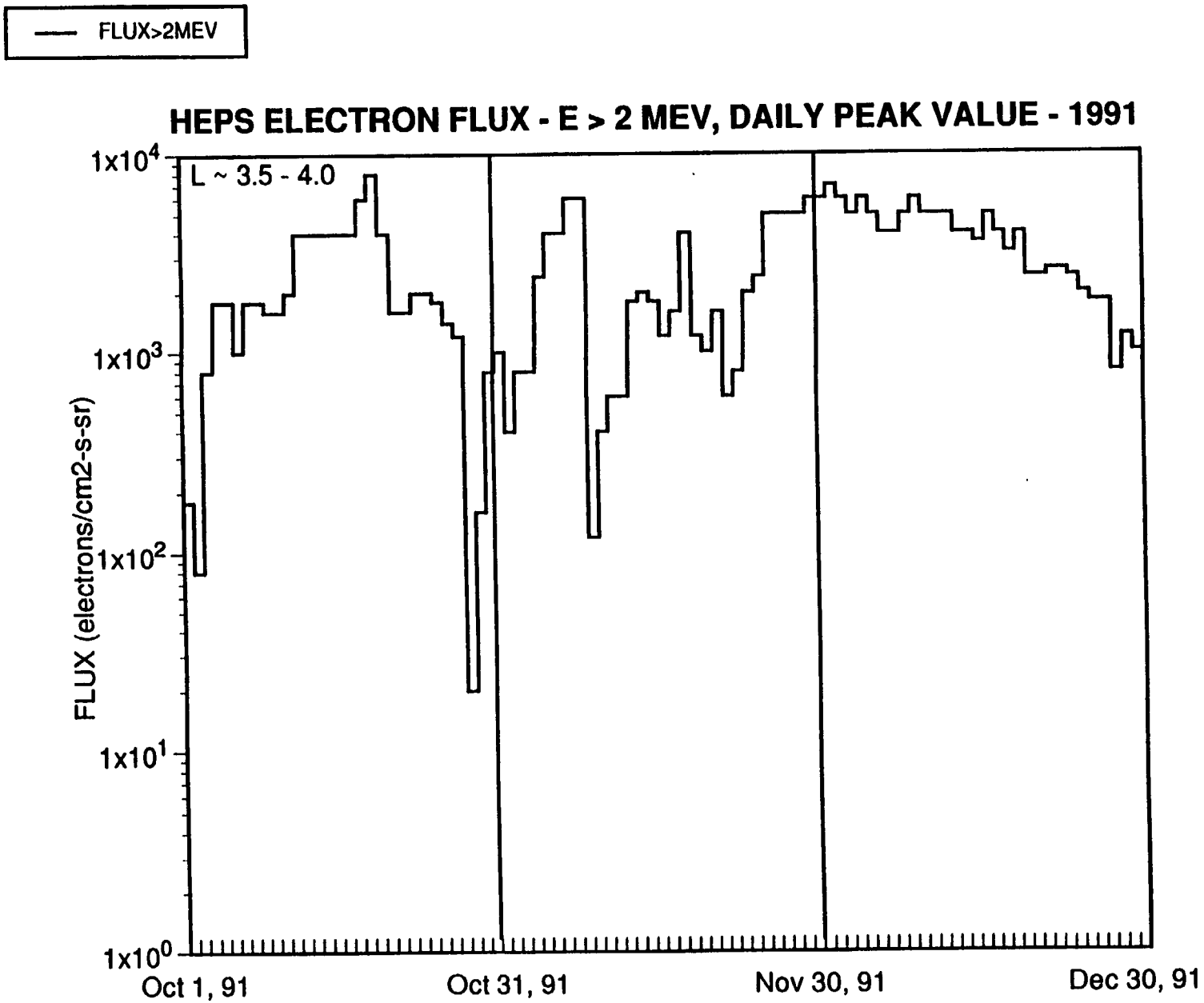
30 Nov. 1995

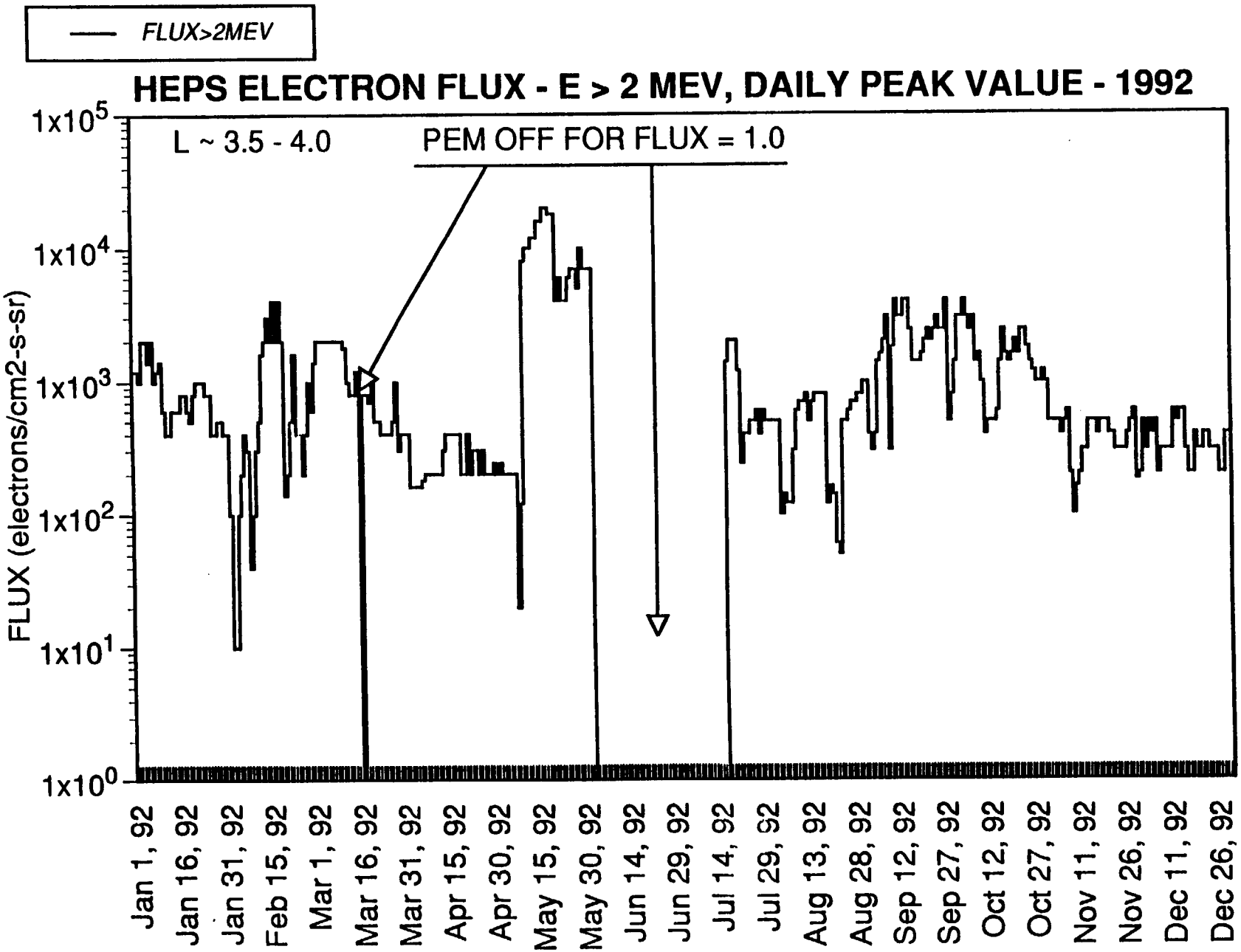
Interim Report - Mesospheric Response to Impacting Relativistic Electrons : Task 1. Ref P.O. SC TDZ0930 F

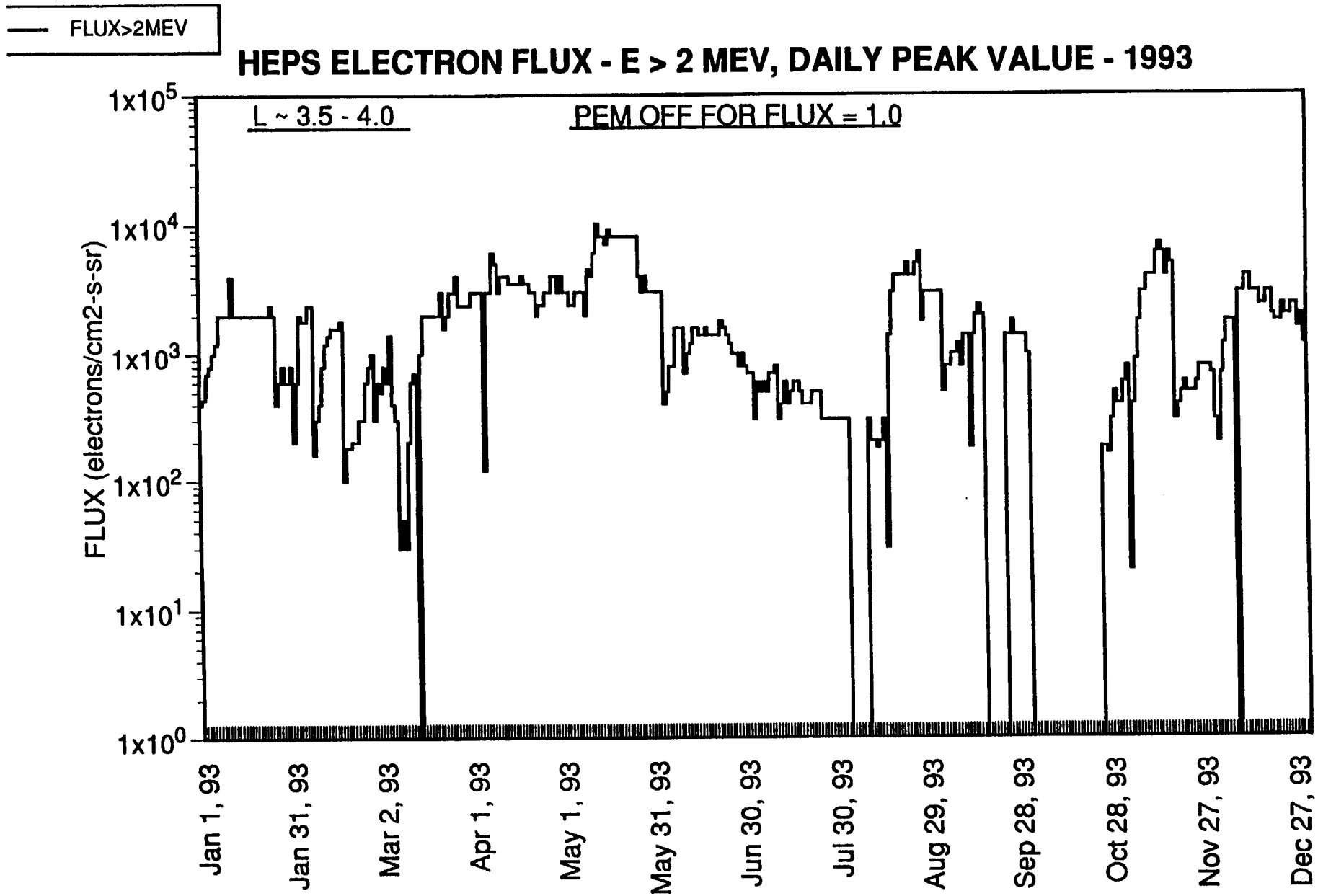
Submitted in completion of Task 1 of SPACERAD statement of work:
Using data from the PEM/HEPS instrument aboard the UARS spacecraft, periods of highly relativistic electron precipitation will be identified, and SPACERAD will join in the selection of specific periods for more detailed analysis.

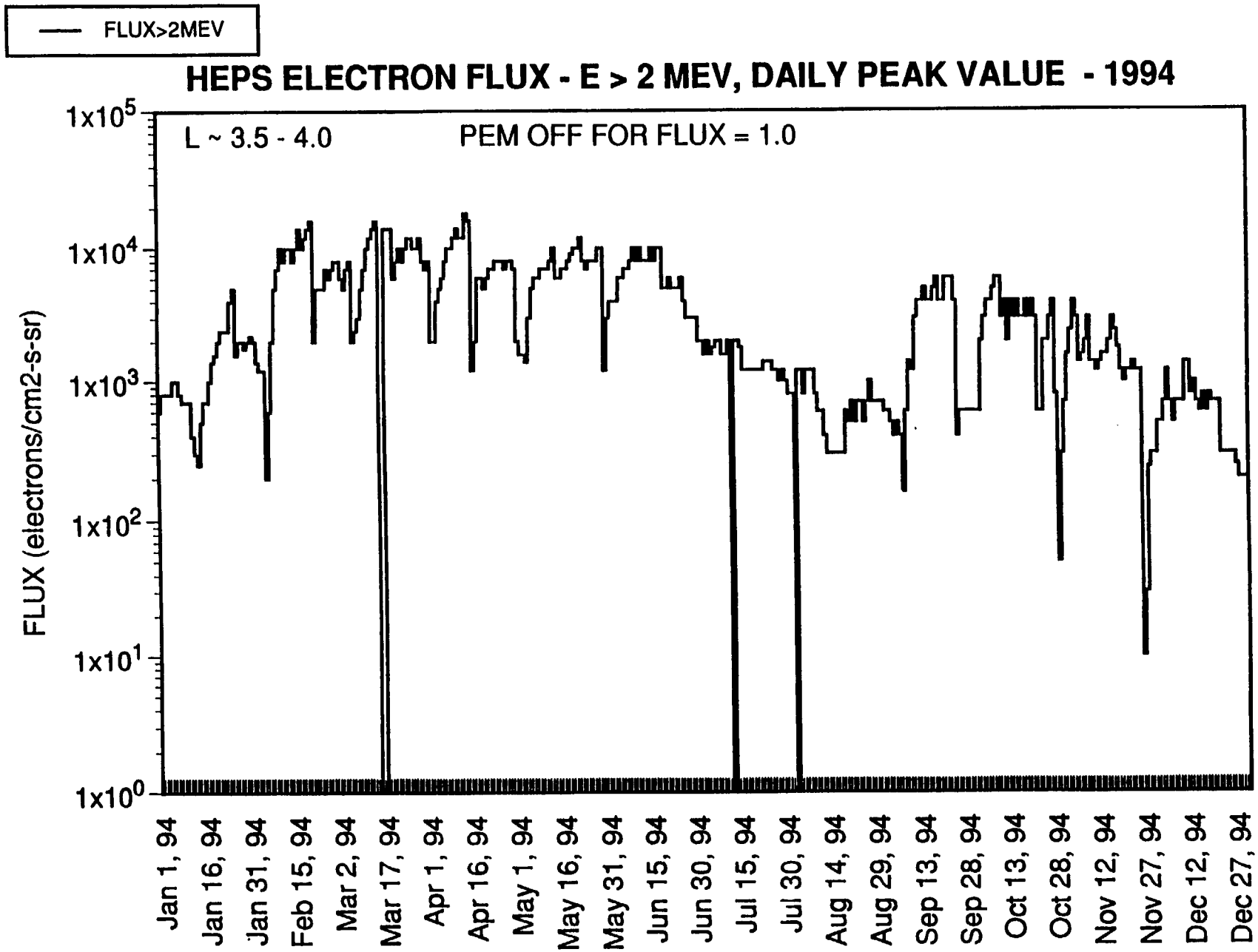
The intensity of relativistic electron fluxes at the UARS spacecraft has been extracted for the time period from instrument turn-on to mid-April 1995 when continuous operation of the HEPS was interrupted due to spacecraft difficulties. Plots of the peak daily flux of electrons with energies greater than 2 MeV are attached.

From the plots, several periods of high electron flux intensity were selected for suggested study during the operational lifetime of the CLAES instrument with which correlations of electron precipitation are to be sought. A summary of these suggested intervals is also attached.


FLUX>2MEV
HEPS ELECTRON FLUX - E > 2 MEV, DAILY PEAK VALUE - 1991
L ~ 3.5 - 4.0
FLUX (electrons/cm2-s-sr)
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
Oct 1, 91
Oct 31, 91
Nov 30, 91
Dec 30, 91


FLUX>2MEV
HEPS ELECTRON FLUX - E > 2 MEV, DAILY PEAK VALUE - 1992
L ~ 3.5 - 4.0
PEM OFF FOR FLUX = 1.0
FLUX (electrons/cm2-s-sr)
1x10^5
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
Jan 1, 92
Jan 16, 92
Jan 31, 92
Feb 15, 92
Mar 1, 92
Mar 16, 92
Mar 31, 92
Apr 15, 92
Apr 30, 92
May 15, 92
May 30, 92
Jun 14, 92
Jun 29, 92
Jul 14, 92
Jul 29, 92
Aug 13, 92
Aug 28, 92
Sep 12, 92
Sep 27, 92
Oct 12, 92
Oct 27, 92
Nov 11, 92
Nov 26, 92
Dec 11, 92
Dec 26, 92


FLUX>2MEV
HEPS ELECTRON FLUX - E > 2 MEV, DAILY PEAK VALUE - 1993
L ~ 3.5 - 4.0
PEM OFF FOR FLUX = 1.0
FLUX (electrons/cm2-s-sr)
1x10^5
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
Jan 1, 93
Jan 31, 93
Mar 2, 93
Apr 1, 93
May 1, 93
May 31, 93
Jun 30, 93
Jul 30, 93
Aug 29, 93
Sep 28, 93
Oct 28, 93
Nov 27, 93
Dec 27, 93


FLUX>2MEV
HEPS ELECTRON FLUX - E > 2 MEV, DAILY PEAK VALUE - 1994
L ~ 3.5 - 4.0
PEM OFF FOR FLUX = 1.0
FLUX (electrons/cm2-s-sr)
1x10^5
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
Jan 1, 94
Jan 16, 94
Jan 31, 94
Feb 15, 94
Mar 2, 94
Mar 17, 94
Apr 1, 94
Apr 16, 94
May 1, 94
May 16, 94
May 31, 94
Jun 15, 94
Jun 30, 94
Jul 15, 94
Jul 30, 94
Aug 14, 94
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Sep 13, 94
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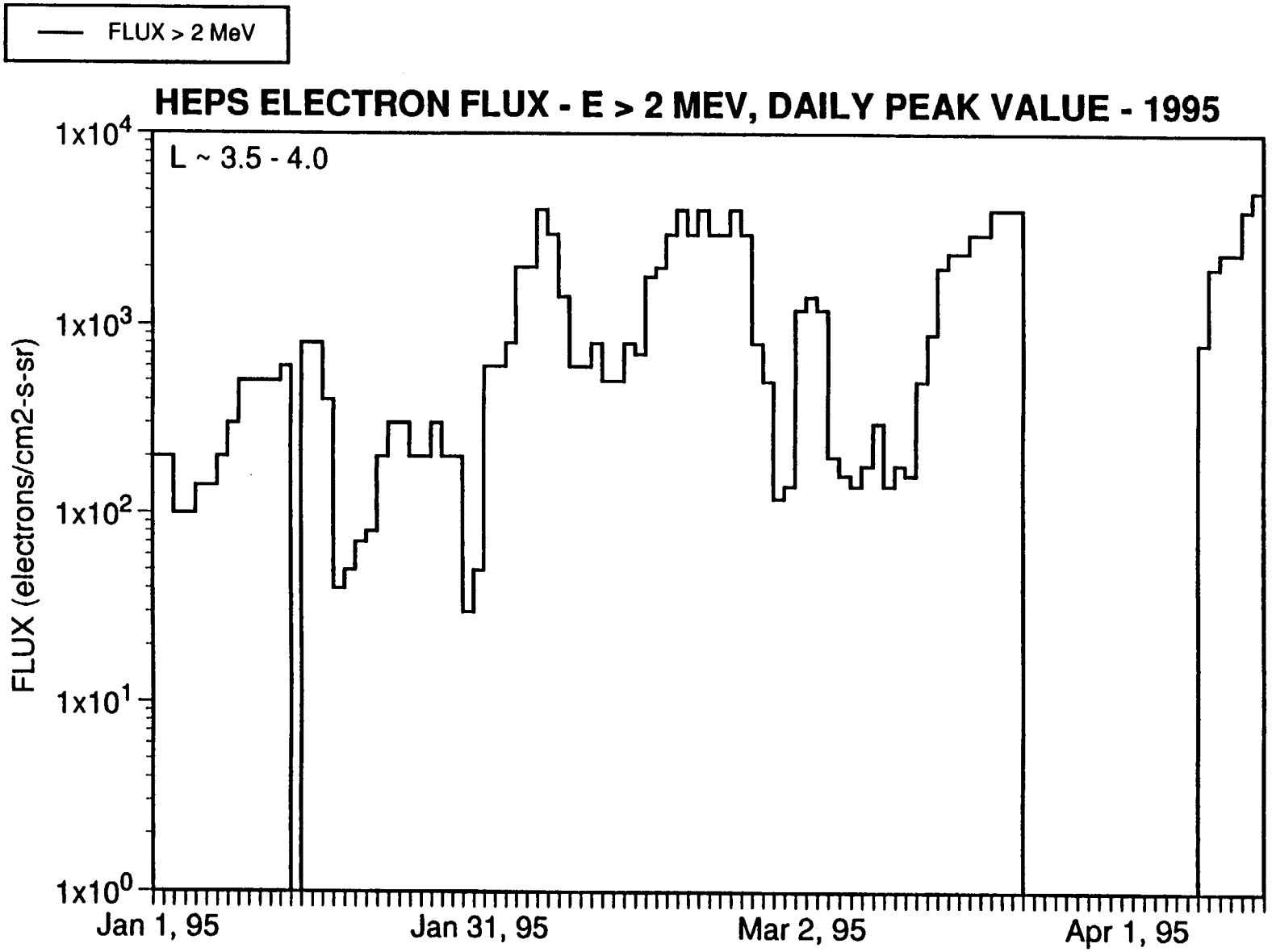
Oct 13, 94
Oct 28, 94
Nov 12, 94
Nov 27, 94
Dec 12, 94
Dec 27, 94


FLUX > 2 MeV
HEPS ELECTRON FLUX - E > 2 MEV, DAILY PEAK VALUE - 1995
L ~ 3.5 - 4.0
FLUX (electrons/cm2-s-sr)
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
Jan 1, 95
Jan 31, 95
Mar 2, 95
Apr 1, 95

Mesospheric Response to Impacting Relativistic Electrons

SUGGESTED INTERVALS OF HRE FLUX FOR DETAILED STUDY

First priority - with CLAES data

DATE	UARS DAYS	PEAK > 2 MEV TRAP FLUX
1. May 11-21, 1992	243 - 253	2. X 10^4 / cm^2-s-sr.
2. Oct. 10-20, 1991	29 - 39	8. X 10^3
3. Nov. 24-Dec. 21, 1991	74 - 101	7. X 10^3
4. Nov. 4-8, 1991	54 - 58	6. X 10^3
5. Apr. 6-May 3, 1993	573 - 600	6. X 10^3

Appendix B

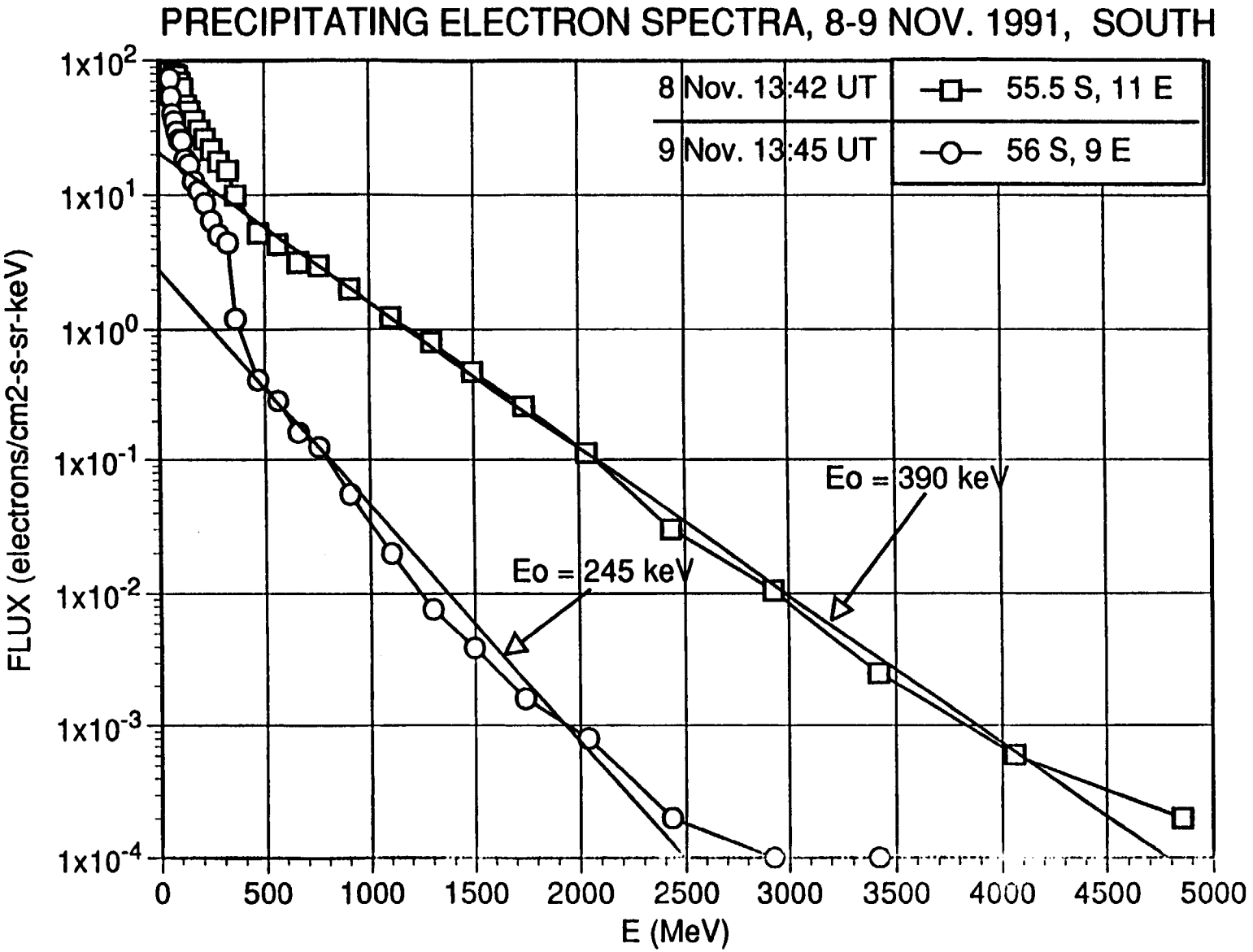
Interim Report

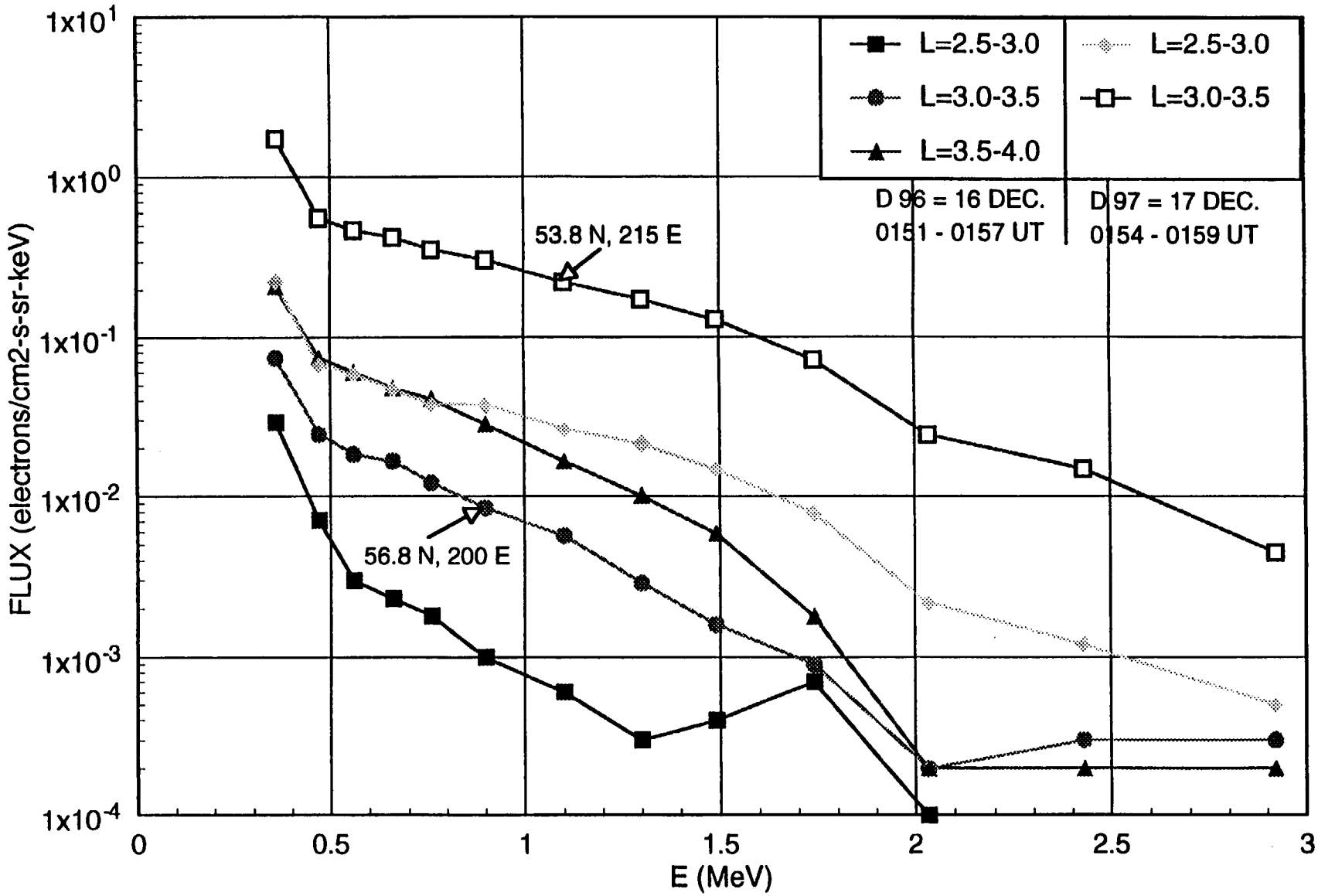
26 Feb. 1996

Task 2 in Statement of Work for support of project:
Mesospheric Response to Impacting Relativistic Electrons
Ref. P.O.# SC PDZ 0931F

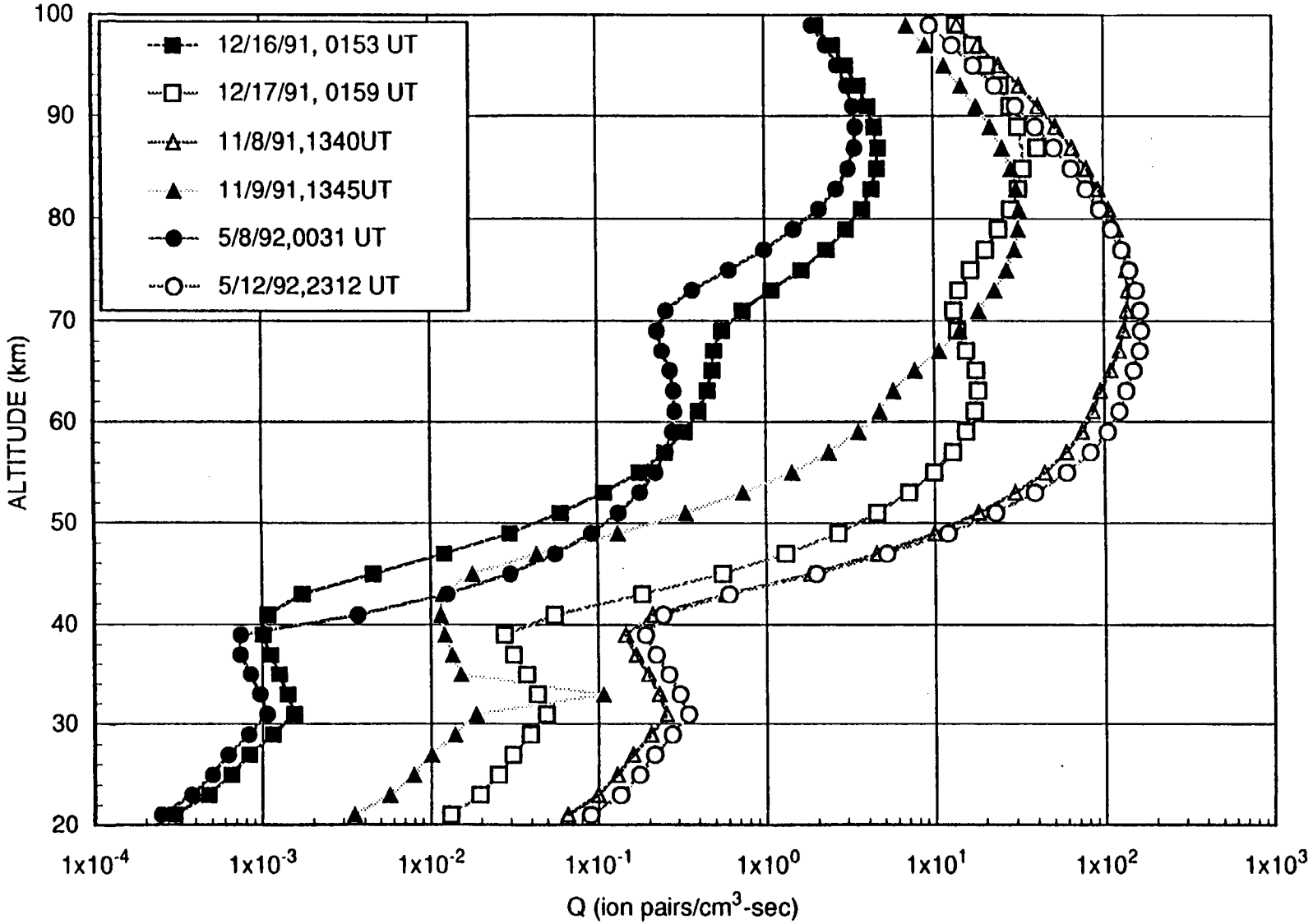
Energy spectra, spatial and temporal distributions of precipitating relativistic electrons and resulting ion production profiles have been obtained from PEM/HEPS data in the time periods identified in Task 1 of this effort as most promising for correlation with measurements of ozone by other instruments on board the UARS spacecraft. These results have been transmitted to LMMS Dept. 91-20 and to Dr. R. A. Goldberg of NASA, and figures illustrating the measurements are attached herewith.

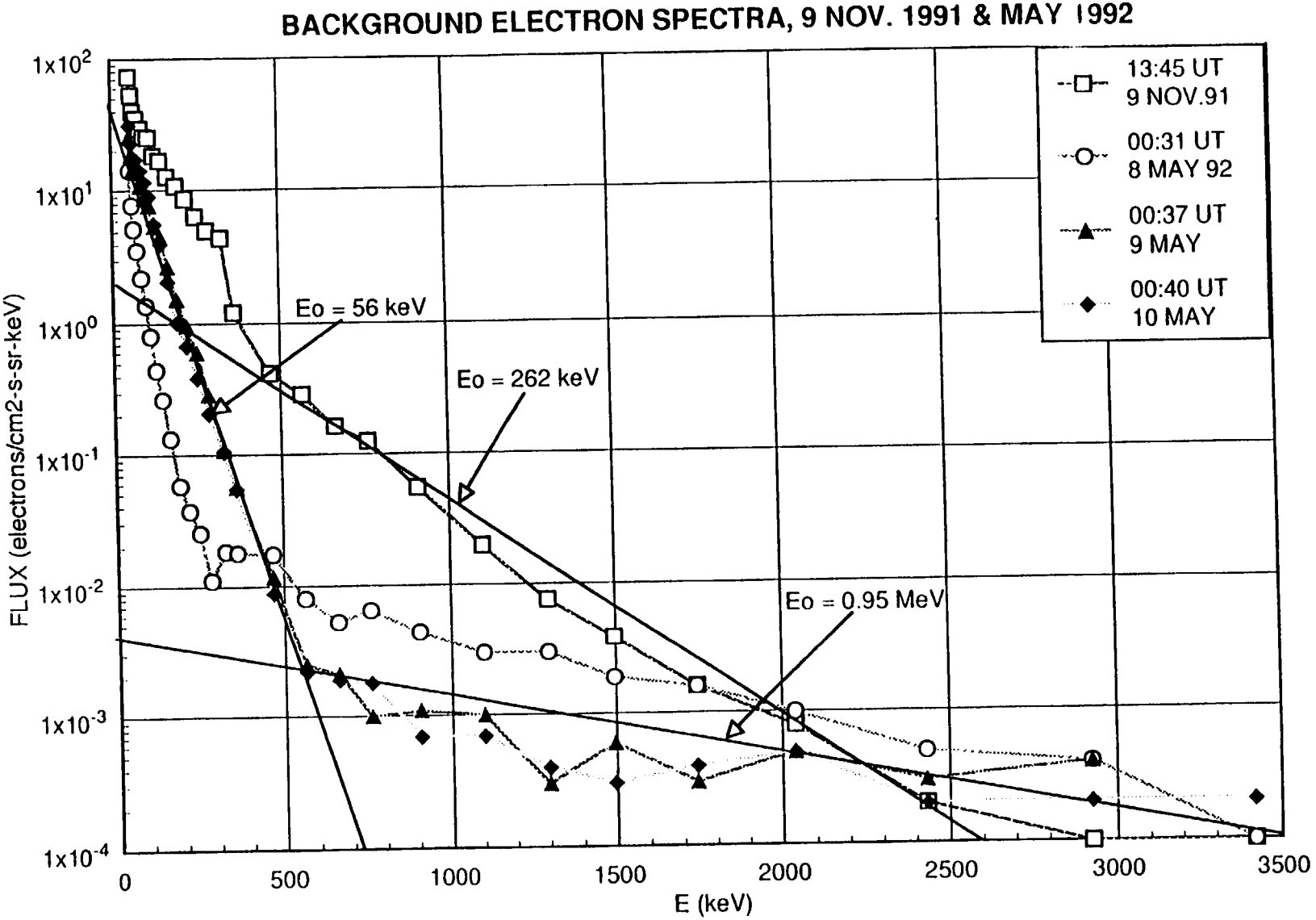
The periods for detailed analysis include the most intense fluxes of relativistic electrons observed wiht the HEPS instrument (May 12 - 20, 1992) and other periods with large changes in the fluxes of precipitating relativistic electrons within a few days. Times of both northward and southward observation by CLAES are included, but the magnetic local times of the flux observation periods were all between 0900 and 2000 hours.

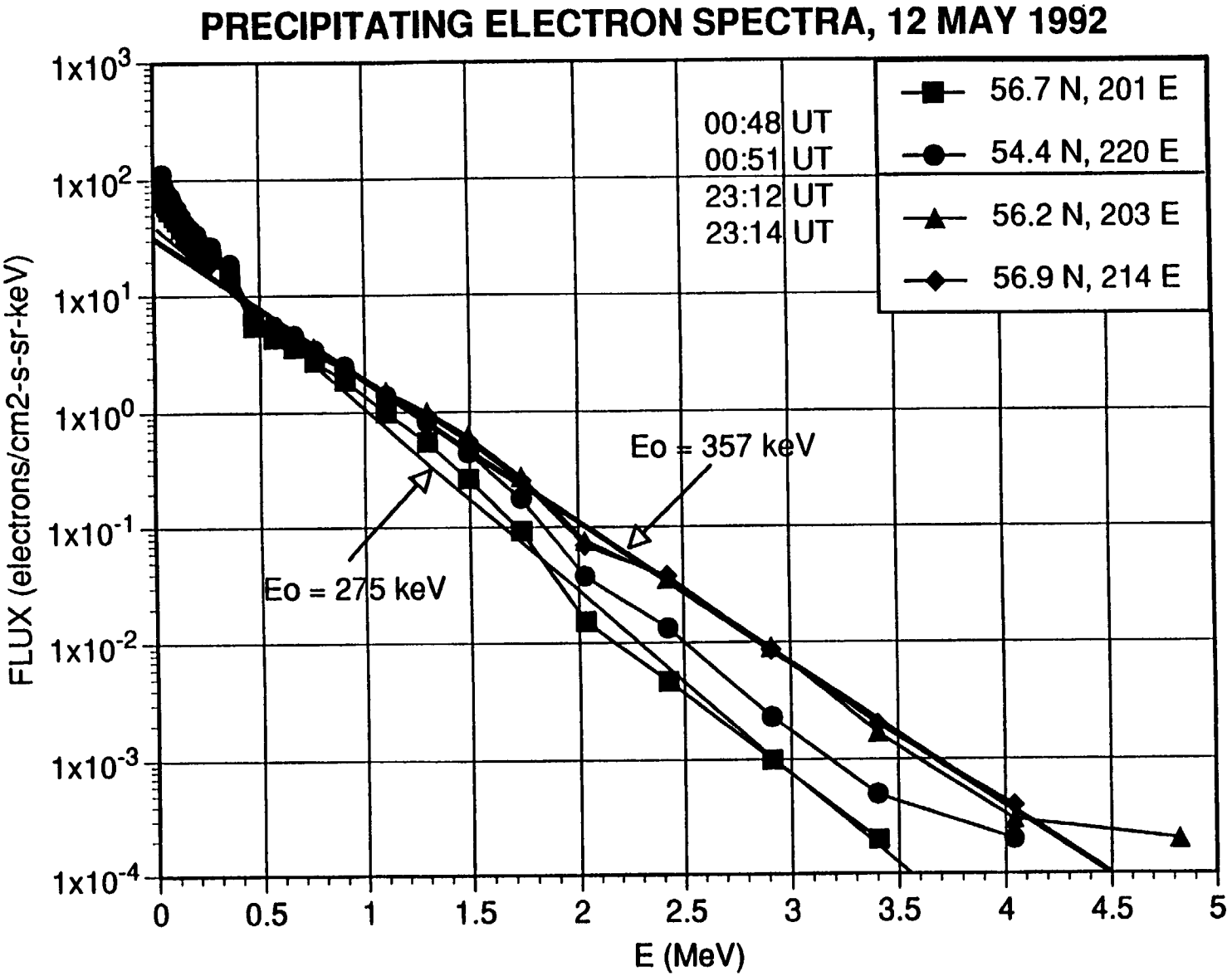

PRECIPITATING ELECTRON SPECTRA, 8-9 NOV. 1991, SOUTH
8 Nov. 13:42 UT
55.5 S, 11 E
9 Nov. 13:45 UT
56 S, 9 E
Eo = 390 keV
Eo = 245 keV
FLUX (electrons/cm2-s-sr-keV)
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
E (MeV)

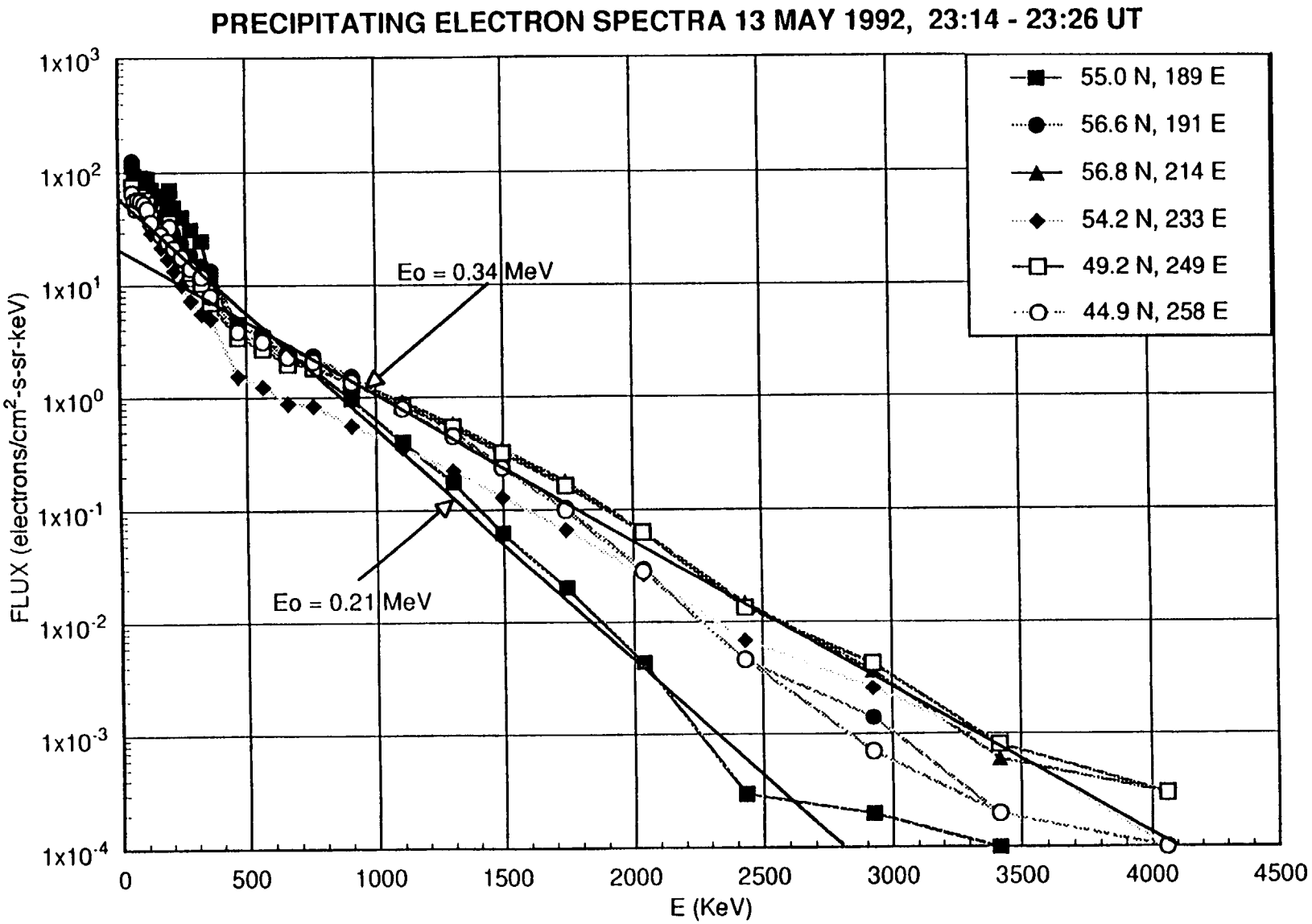

D 96 - 97 PRECIPITATING ELECTRONS : DLC REGION
FLUX (electrons/cm2-s-sr-keV)
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
0.5
1
1.5
2
2.5
3
E (MeV)
L=2.5-3.0
L=3.0-3.5
L=3.5-4.0
L=2.5-3.0
L=3.0-3.5
D 96 = 16 DEC.
0151 - 0157 UT
D 97 = 17 DEC.
0154 - 0159 UT
53.8 N, 215 E
56.8 N, 200 E

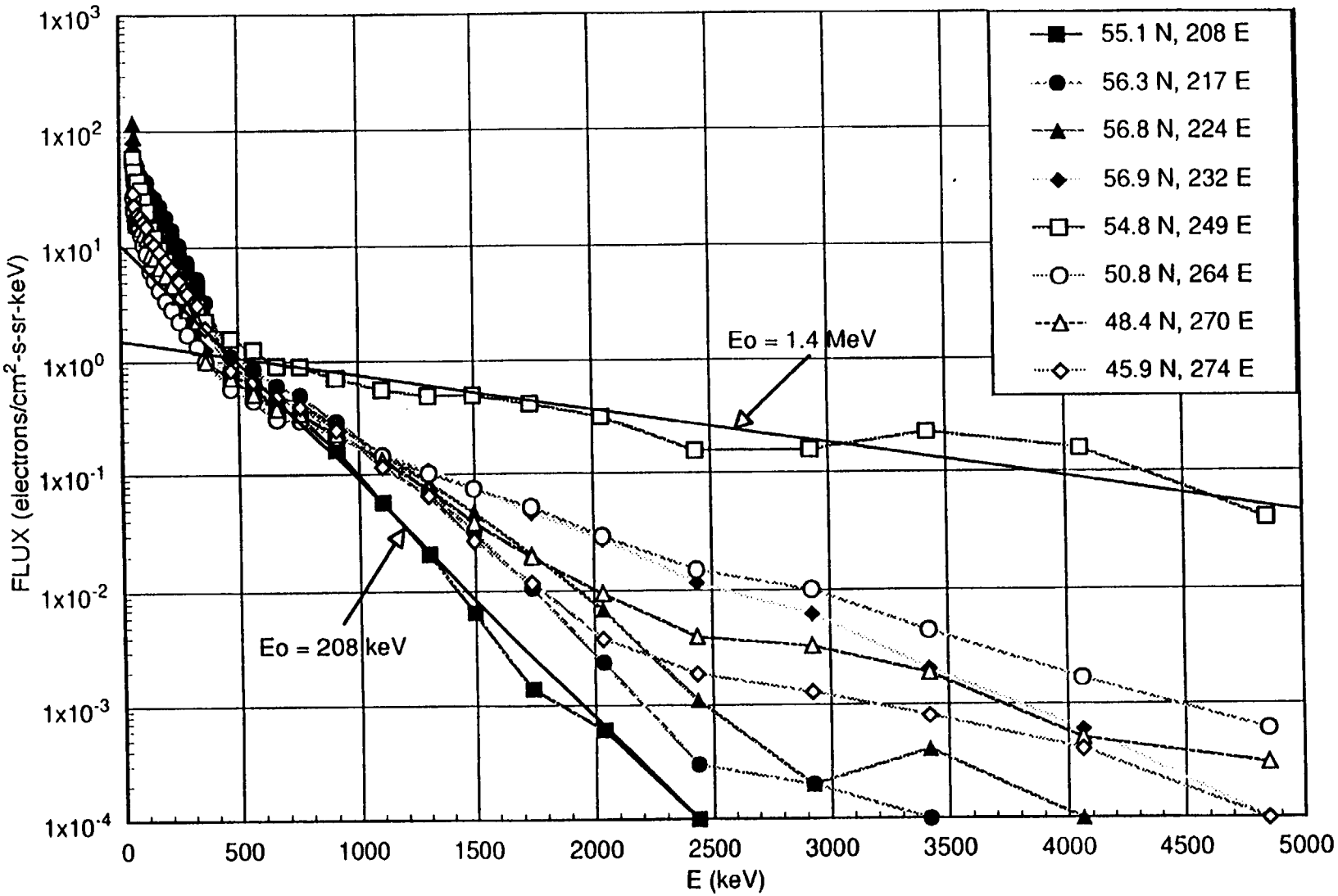
ION PRODUCTION PROFILES, 8 - 9 NOV. , 16 - 17 DEC. 1991, 8 &12 MAY 1992

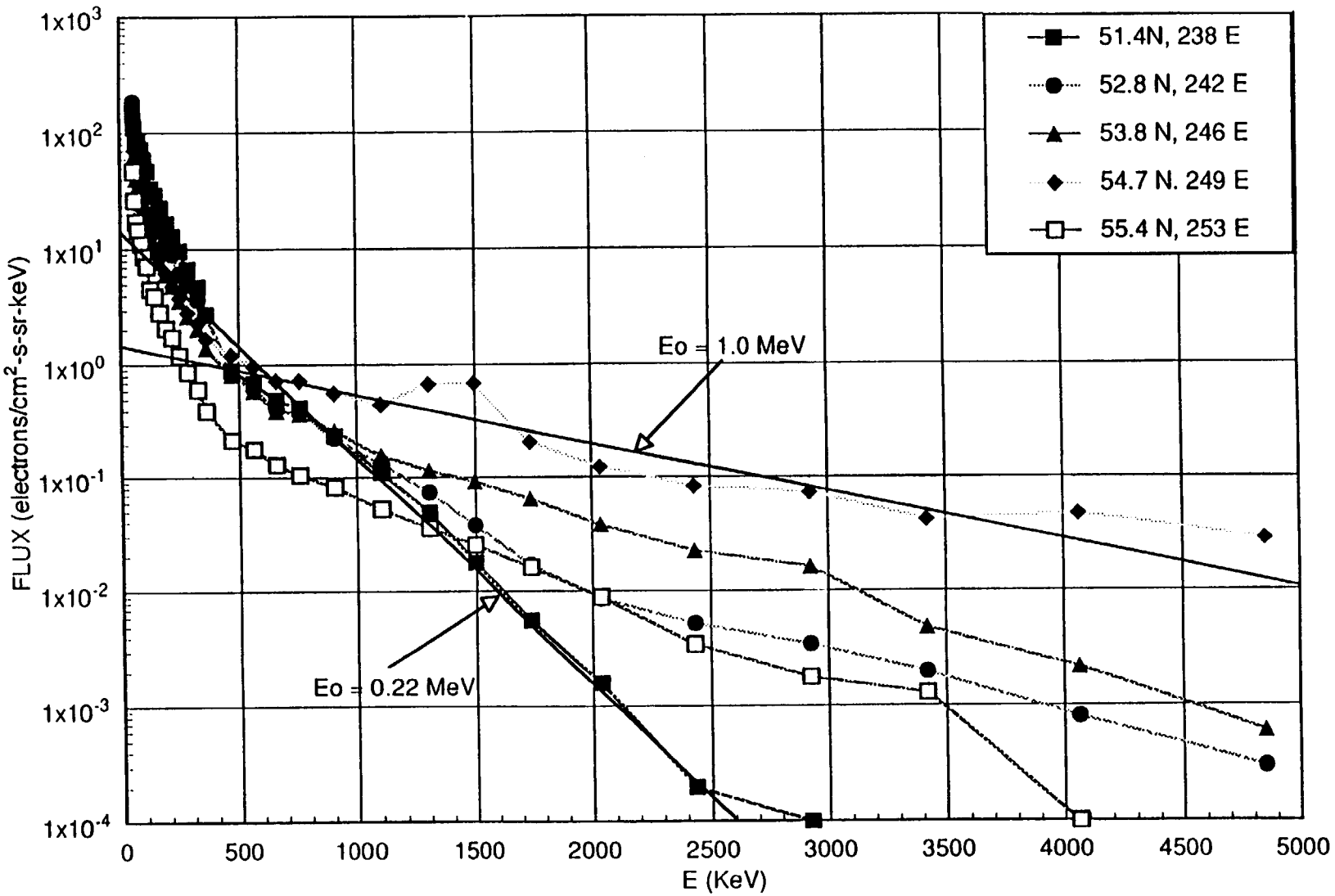


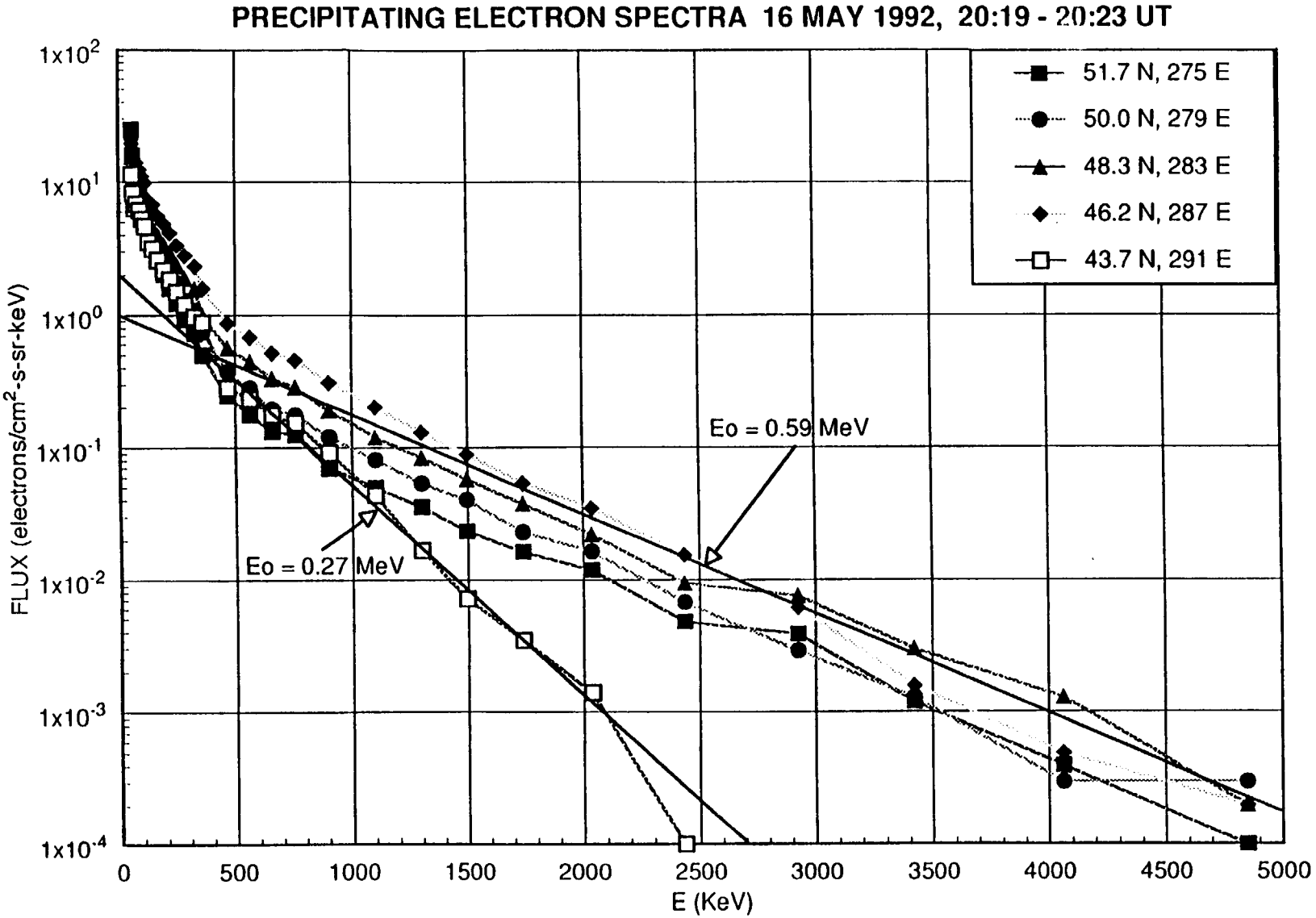

BACKGROUND ELECTRON SPECTRA, 9 NOV. 1991 & MAY 1992
13:45 UT
9 NOV.91
00:31 UT
8 MAY 92
00:37 UT
9 MAY
00:40 UT
10 MAY
Eo = 56 keV
Eo = 262 keV
Eo = 0.95 MeV
FLUX (electrons/cm2-s-sr-keV)
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
E (keV)

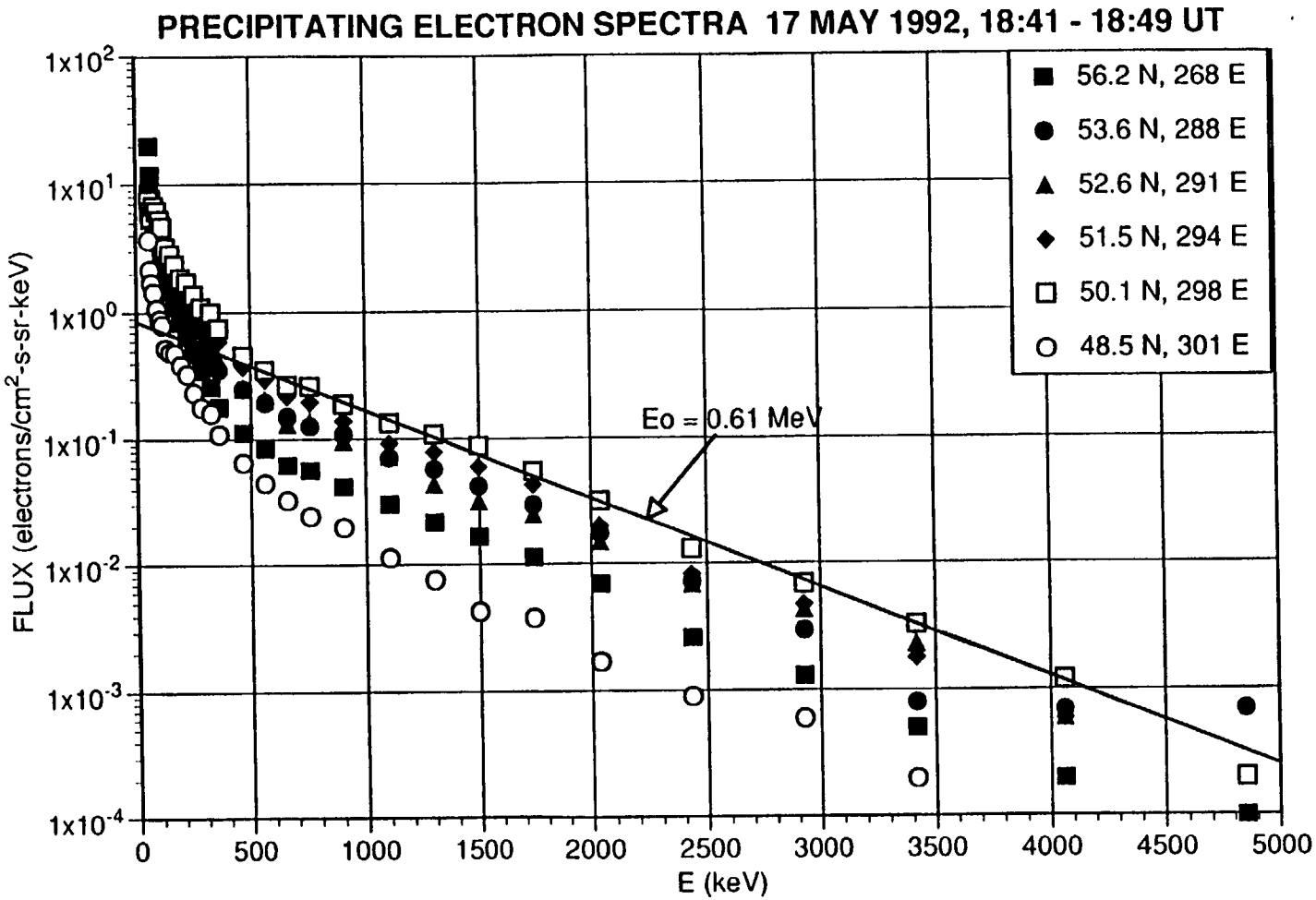

PRECIPITATING ELECTRON SPECTRA, 12 MAY 1992
FLUX (electrons/cm2-s-sr-keV)
E (MeV)
00:48 UT
00:51 UT
23:12 UT
23:14 UT
56.7 N, 201 E
54.4 N, 220 E
56.2 N, 203 E
56.9 N, 214 E
Eo = 357 keV
Eo = 275 keV
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

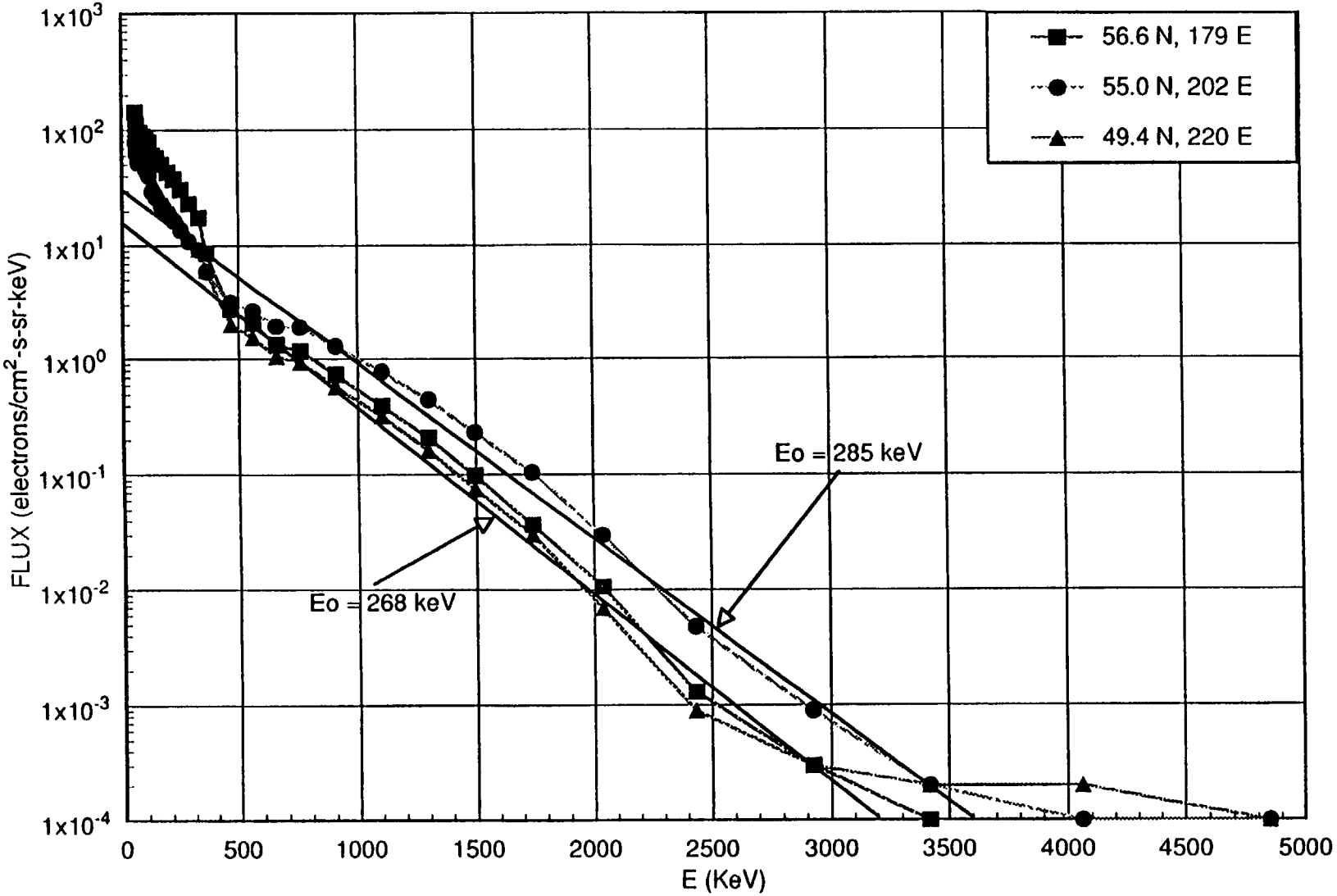

PRECIPITATING ELECTRON SPECTRA 13 MAY 1992, 23:14 - 23:26 UT
55.0 N, 189 E
56.6 N, 191 E
56.8 N, 214 E
54.2 N, 233 E
49.2 N, 249 E
44.9 N, 258 E
Eo = 0.34 MeV
Eo = 0.21 MeV
FLUX (electrons/cm2-s-sr-keV)
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
E (KeV)

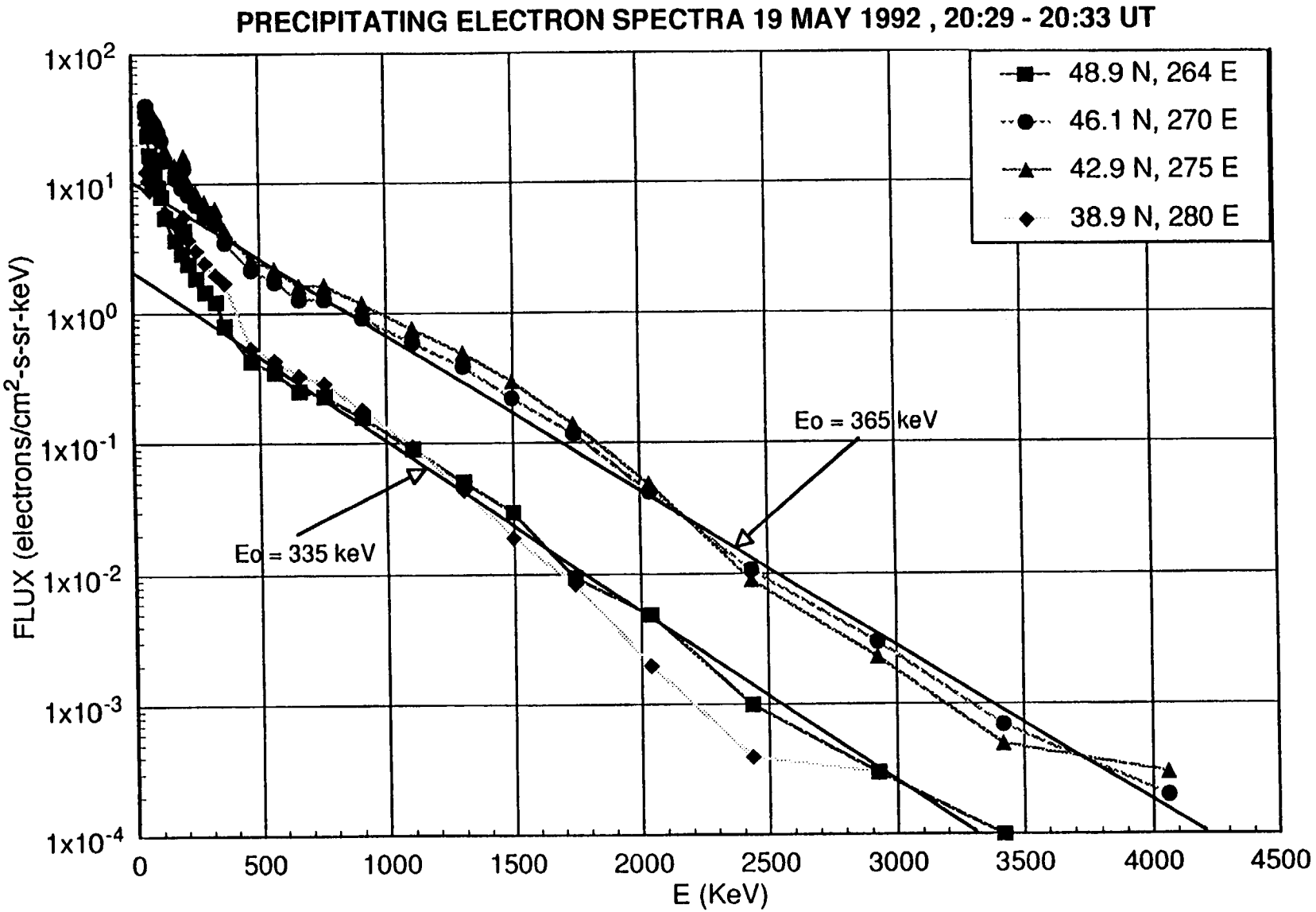

PRECIPITATING ELECTRON SPECTRA 14 MAY, 1992 - 21:40-21:52 UT
FLUX (electrons/cm^2-s-sr-keV)
1x10^3
1x10^2
1x10^1
1x10^0
1x10^{-1}
1x10^{-2}
1x10^{-3}
1x10^{-4}
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
E (keV)
55.1 N, 208 E
56.3 N, 217 E
56.8 N, 224 E
56.9 N, 232 E
54.8 N, 249 E
50.8 N, 264 E
48.4 N, 270 E
45.9 N, 274 E
Eo = 1.4 MeV
Eo = 208 keV

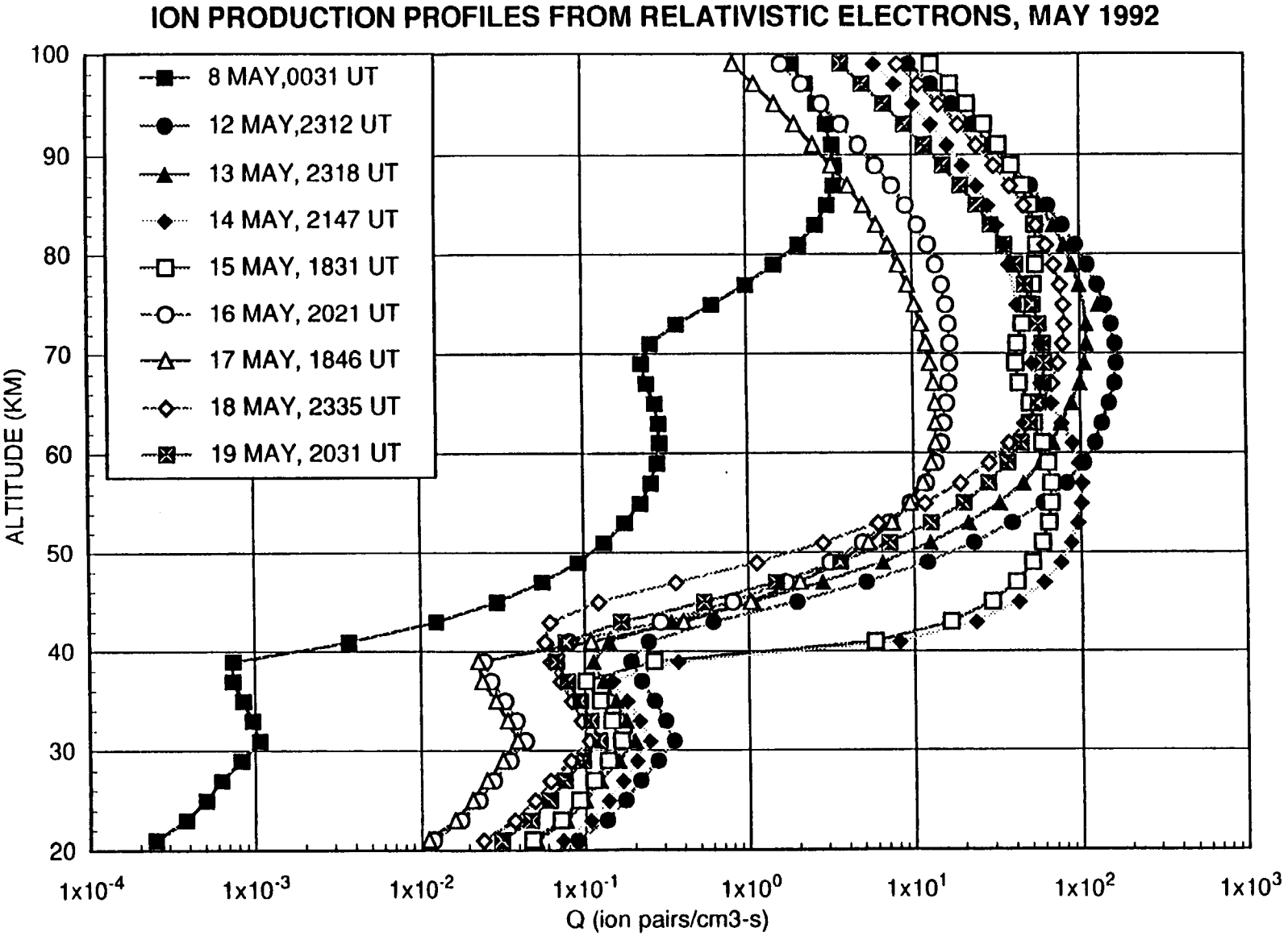

PRECIPITATING ELECTRON SPECTRA, 15 MAY 1992 - 18:29-18:31 UT
51.4N, 238 E
52.8 N, 242 E
53.8 N, 246 E
54.7 N. 249 E
55.4 N, 253 E
Eo = 1.0 MeV
Eo = 0.22 MeV
FLUX (electrons/cm²-s-sr-keV)
E (KeV)
1x10³
1x10²
1x10¹
1x10⁰
1x10⁻¹
1x10⁻²
1x10⁻³
1x10⁻⁴
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


PRECIPITATING ELECTRON SPECTRA 16 MAY 1992, 20:19 - 20:23 UT
51.7 N, 275 E
50.0 N, 279 E
48.3 N, 283 E
46.2 N, 287 E
43.7 N, 291 E
Eo = 0.59 MeV
Eo = 0.27 MeV
FLUX (electrons/cm2-s-sr-keV)
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
E (KeV)


PRECIPITATING ELECTRON SPECTRA 17 MAY 1992, 18:41 - 18:49 UT
56.2 N, 268 E
53.6 N, 288 E
52.6 N, 291 E
51.5 N, 294 E
50.1 N, 298 E
48.5 N, 301 E
Eo = 0.61 MeV
FLUX (electrons/cm2-s-sr-keV)
E (keV)
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


PRECIPITATING ELECTRON SPECTRA 18 MAY, 1992 - 23:31-23:38 UT
56.6 N, 179 E
55.0 N, 202 E
49.4 N, 220 E
Eo = 285 keV
Eo = 268 keV
FLUX (electrons/cm2-s-sr-keV)
E (KeV)
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


PRECIPITATING ELECTRON SPECTRA 19 MAY 1992 , 20:29 - 20:33 UT
48.9 N, 264 E
46.1 N, 270 E
42.9 N, 275 E
38.9 N, 280 E
Eo = 365 keV
Eo = 335 keV
FLUX (electrons/cm2-s-sr-keV)
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
E (KeV)


ION PRODUCTION PROFILES FROM RELATIVISTIC ELECTRONS, MAY 1992
8 MAY,0031 UT
12 MAY,2312 UT
13 MAY, 2318 UT
14 MAY, 2147 UT
15 MAY, 1831 UT
16 MAY, 2021 UT
17 MAY, 1846 UT
18 MAY, 2335 UT
19 MAY, 2031 UT
ALTITUDE (KM)
100
90
80
70
60
50
40
30
20
1x10-4
1x10-3
1x10-2
1x10-1
1x100
1x101
1x102
1x103
Q (ion pairs/cm3-s)

Appendix C

1996 Final Report

Mesospheric Response to Impacting Relativistic Electrons

Introduction

The purpose of this investigation is to search for correlation between precipitating high-energy electrons as measured by the High Energy Particle Spectrometer on the Upper Atmosphere Research Satellite and changes in the chemistry of the mesosphere as measured by CLAES and MLS on the same spacecraft. The following tasks are excerpted from the statement of work:

1. Using data from the PEM/HEPS instrument aboard the UARS spacecraft, periods of highly relativistic electron precipitation will be identified, and Spacerad will join in the selection of specific periods for more detailed analysis.

2. Spacerad will provide energy spectra and spatial and temporal distributions of precipitating relativistic electron fluxes based on the PEM/HEPS data for the specific event periods selected in task #1. The results will be provided to distinguish stably trapped, drift loss cone, and bounce loss cone fluxes.

3. Spacerad will contribute to the analysis, presentation, and publication of the initial results of this project.

Task 1

From continuous survey plots of HEPS data, the daily peak flux of trapped electrons with energies > 2 MeV were surveyed for the entire database up to March 1995 and three time periods showing large changes in flux within two days or less were selected for further study. The periods chosen within the operational lifetime of CLAES as an initial criterion were: 1. 8 - 9 November 1991 when a large magnetic storm precipitated the bulk of the relativistic electrons seen at low altitude
2. 16 - 17 December 1991, a modest relativistic electron event
3. 10 - 20 May 1992, the largest relativistic electron flux event in the database

CLAES viewed southward from the spacecraft during the first period and northward during the second and third periods. The magnetic local time during the times of intense electron precipitation was between ~0900 and ~1600 hours for all three periods.

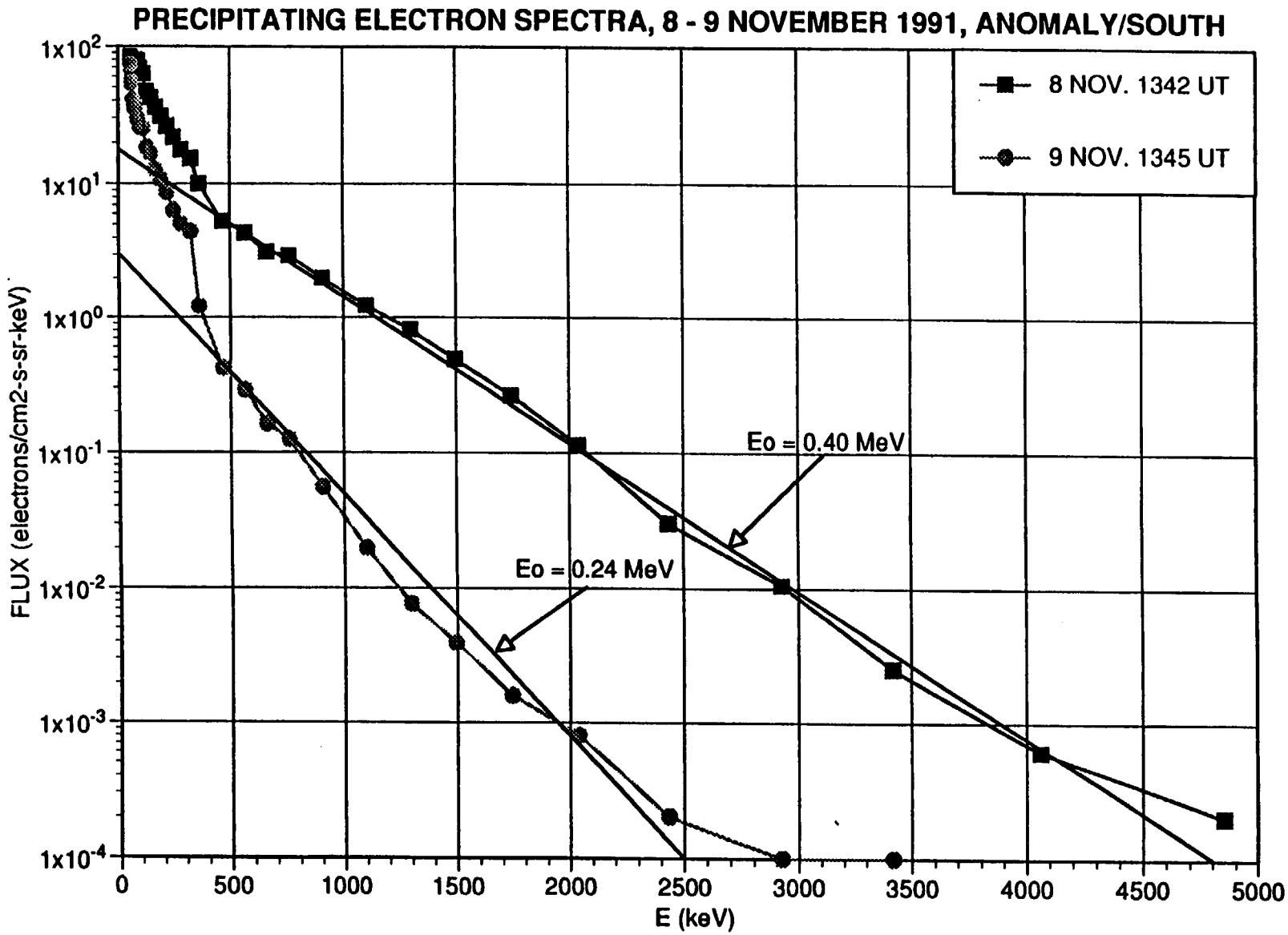
Task 2

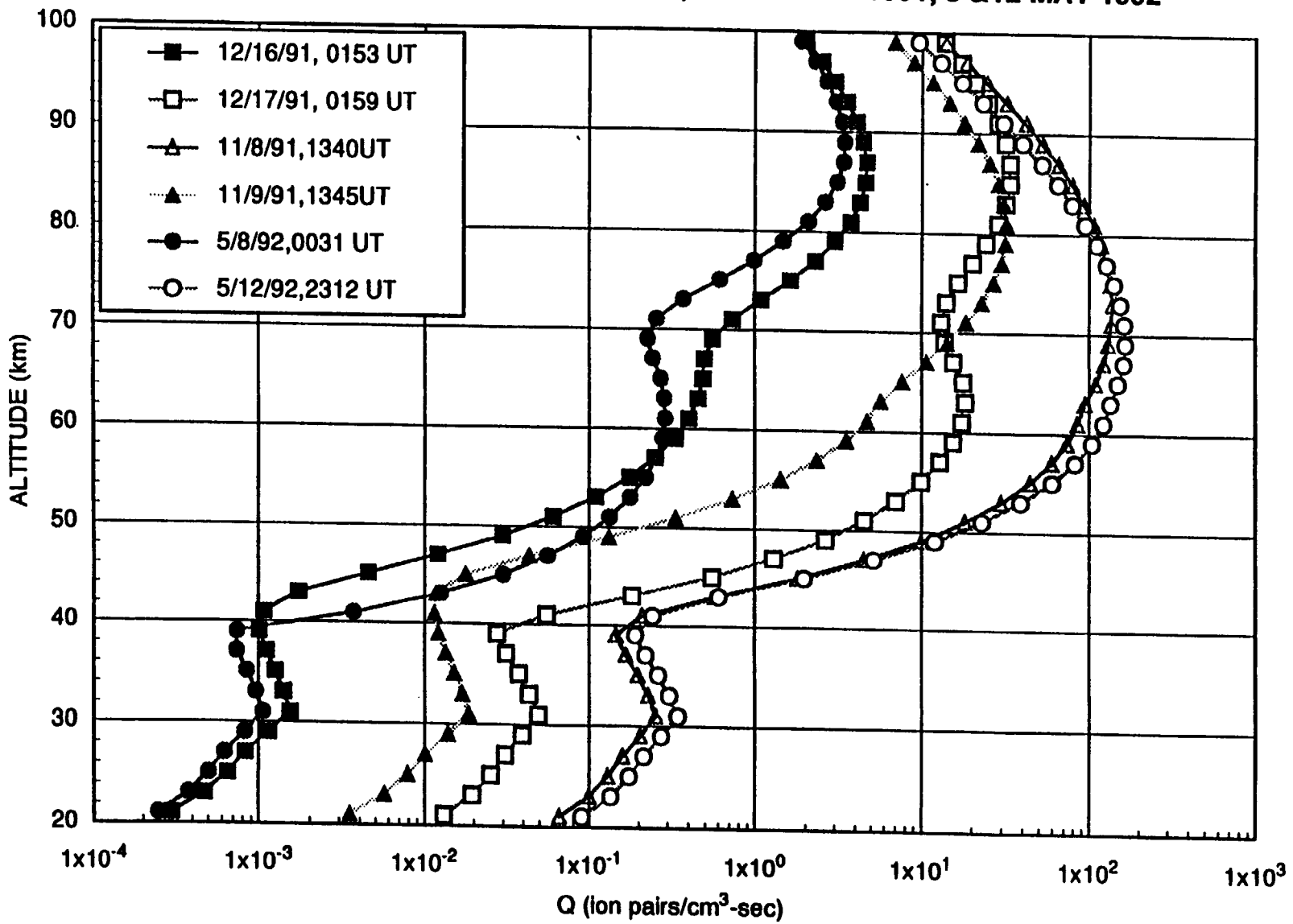
Spatial and temporal distributions of the energy spectra of precipitating relativistic electrons were extracted from the HEPS data for the time periods selected in Task 1. From these, ion production versus altitude profiles were calculated using a code furnished by C. H. Jackman (NASA, Goddard Space Flight Center). Examples of the spectra and corresponding ion production profiles are attached.

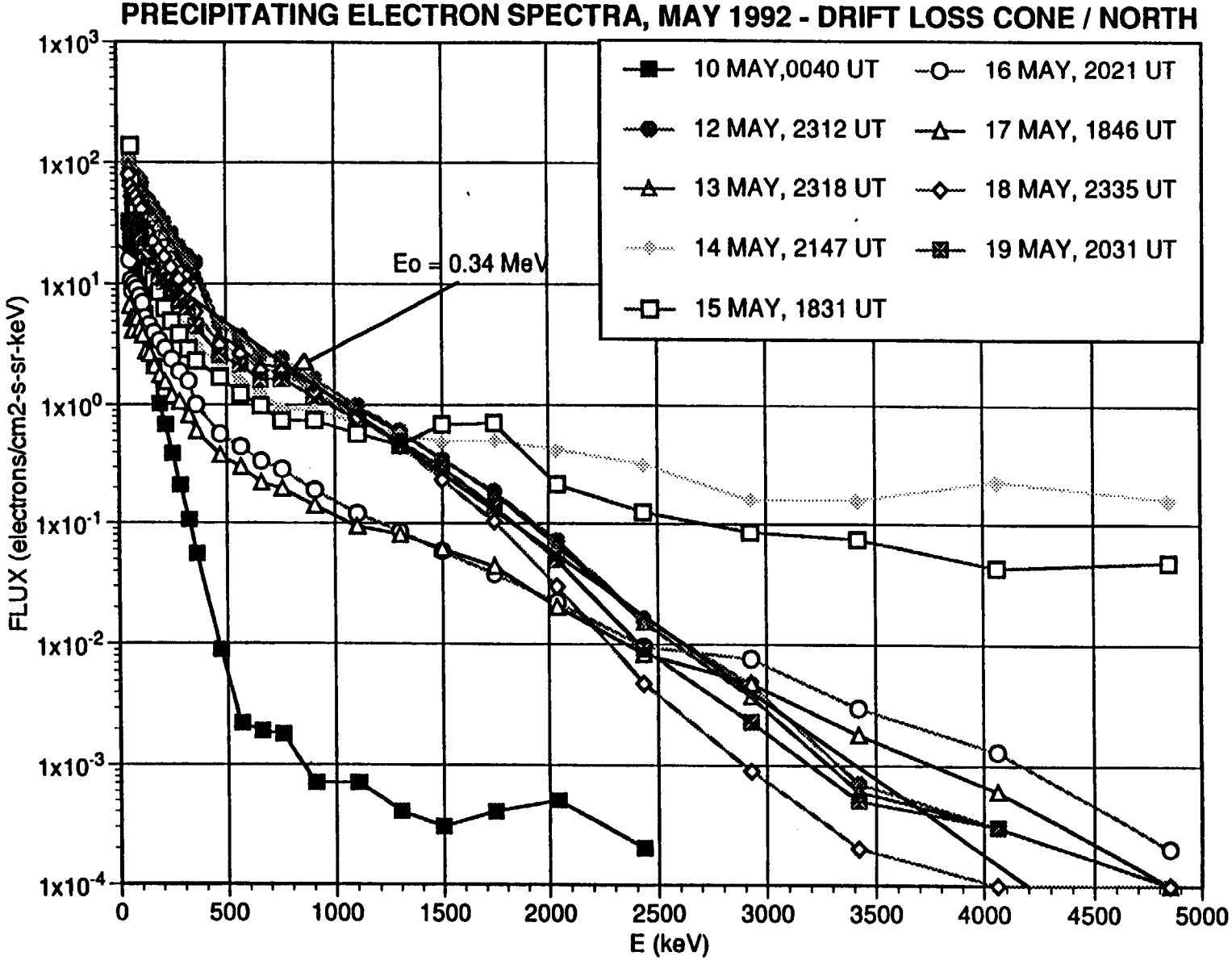
Task 3

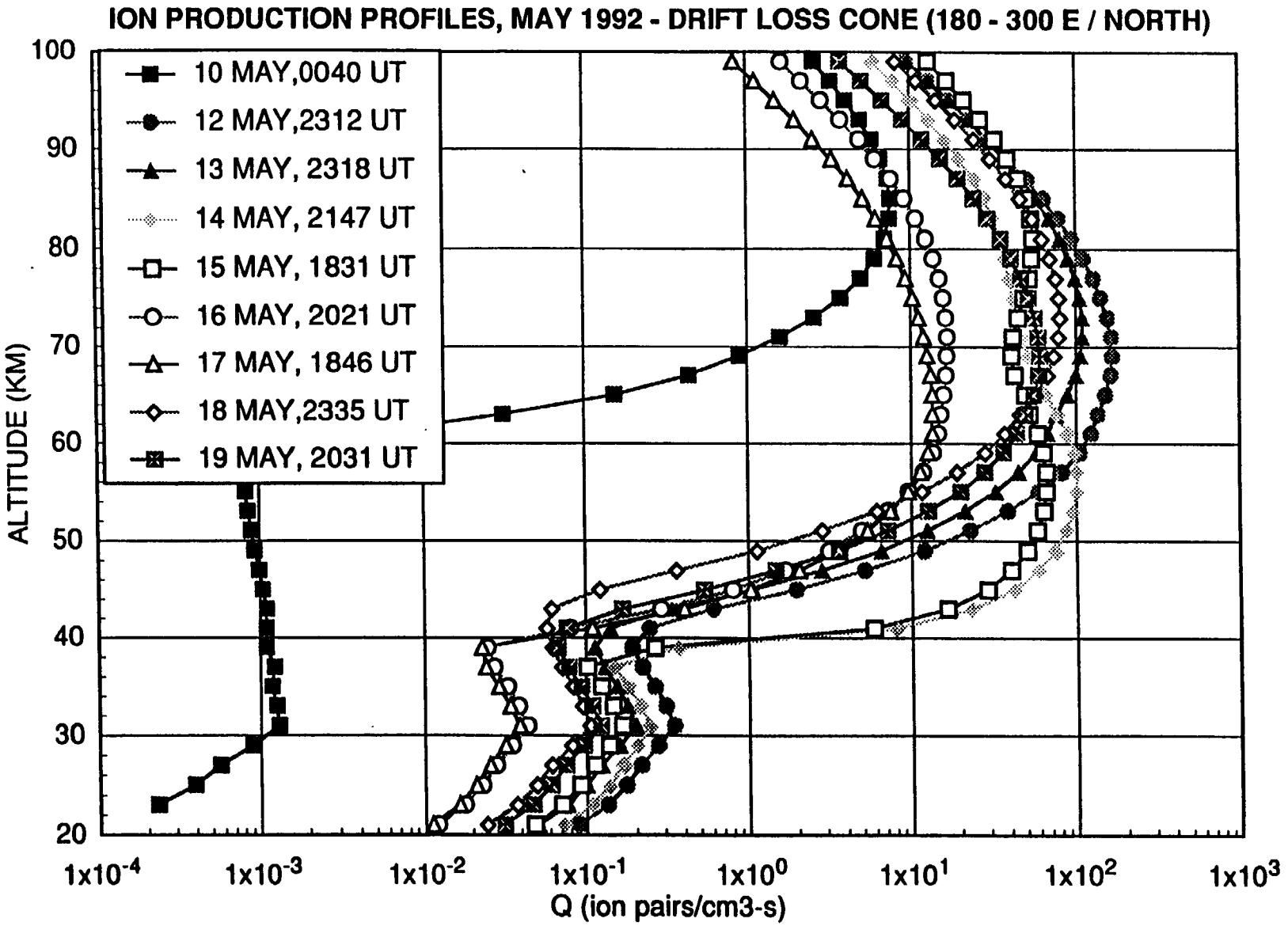
For the highest intensity relativistic electron flux event of May 1992, global plots of trapped as well as precipitating electrons E > 2 MeV were prepared. Detailed spectra were extracted and ion production profiles were calculated during the period for the southern hemisphere region for correlation with HALOE measurements as well as for the drift loss cone region in the north to compare with CLAES and MLS atmospheric measurements.

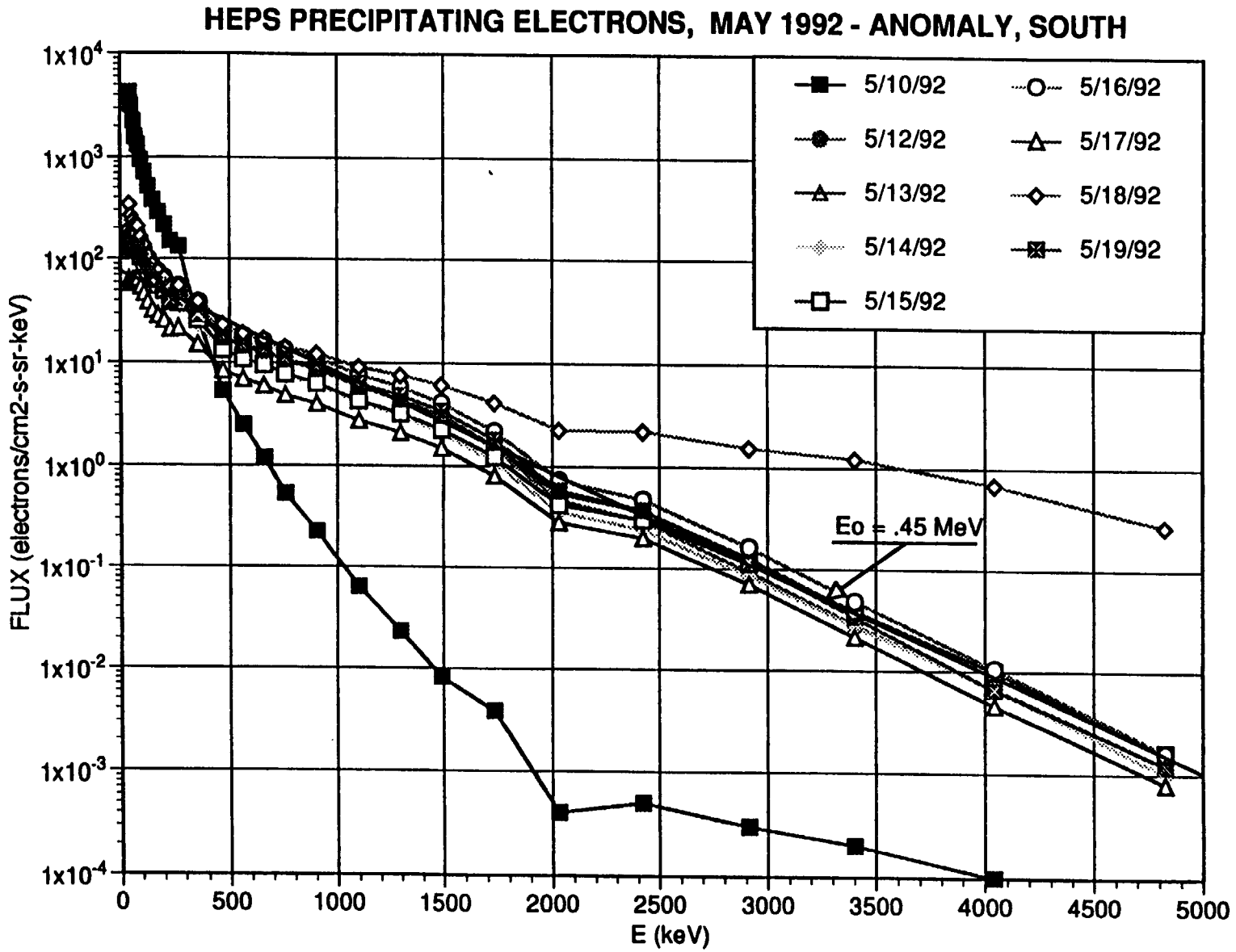
Since the precipitating relativistic electron fluxes in the initially selected data periods were in sunlit conditions making the atmospheric chemistry changes due to the electrons perhaps less discernible from those produced by solar UV, the events with the most pronounced flux changes are the most promising. The rapid removal of relativistic electron fluxes on Nov. 8, 1991 would allow observation of ozone replenishment while the buildup of the fluxes between May 10 and 12, 1992 presents the largest change in ionization seen at altitudes below 60 km in the north and resulting in ozone depletion. The ion profiles due to precipitating electrons show five orders of magnitude increase at nearly the same location between May 10 and May 12, 1992 with the intensity of the ion production at 60 km equal to 10^2 ion-pairs/cm^3-sec.

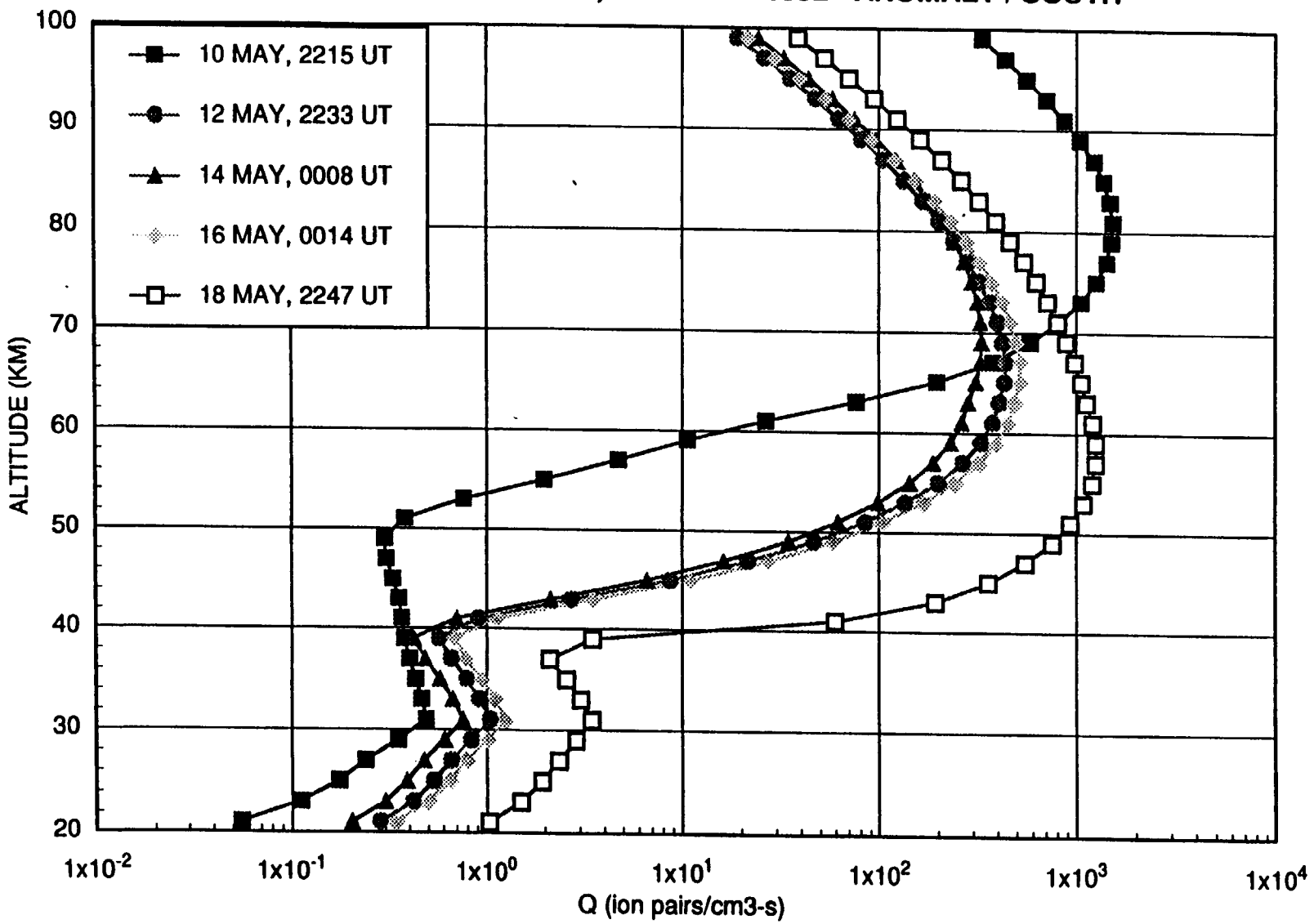

PRECIPITATING ELECTRON SPECTRA, 8 - 9 NOVEMBER 1991, ANOMALY/SOUTH
8 NOV. 1342 UT
9 NOV. 1345 UT
Eo = 0.40 MeV
Eo = 0.24 MeV
FLUX (electrons/cm2-s-sr-keV)
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
E (keV)


ION PRODUCTION PROFILES, 8 - 9 NOV. , 16 - 17 DEC. 1991, 8 &12 MAY 1992
12/16/91, 0153 UT
12/17/91, 0159 UT
11/8/91,1340UT
11/9/91,1345UT
5/8/92,0031 UT
5/12/92,2312 UT
ALTITUDE (km)
100
90
80
70
60
50
40
30
20
1x10-4
1x10-3
1x10-2
1x10-1
1x100
1x101
1x102
1x103
Q (ion pairs/cm3-sec)


PRECIPITATING ELECTRON SPECTRA, MAY 1992 - DRIFT LOSS CONE / NORTH
10 MAY,0040 UT
12 MAY, 2312 UT
13 MAY, 2318 UT
14 MAY, 2147 UT
15 MAY, 1831 UT
16 MAY, 2021 UT
17 MAY, 1846 UT
18 MAY, 2335 UT
19 MAY, 2031 UT
Eo = 0.34 MeV
FLUX (electrons/cm2-s-sr-keV)
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
E (keV)


ION PRODUCTION PROFILES, MAY 1992 - DRIFT LOSS CONE (180 - 300 E / NORTH)
10 MAY,0040 UT
12 MAY,2312 UT
13 MAY, 2318 UT
14 MAY, 2147 UT
15 MAY, 1831 UT
16 MAY, 2021 UT
17 MAY, 1846 UT
18 MAY,2335 UT
19 MAY, 2031 UT
ALTITUDE (KM)
100
90
80
70
60
50
40
30
20
1x10-4
1x10-3
1x10-2
1x10-1
1x100
1x101
1x102
1x103
Q (ion pairs/cm3-s)


HEPS PRECIPITATING ELECTRONS, MAY 1992 - ANOMALY, SOUTH
FLUX (electrons/cm2-s-sr-keV)
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
E (keV)
5/10/92
5/12/92
5/13/92
5/14/92
5/15/92
5/16/92
5/17/92
5/18/92
5/19/92
Eo = .45 MeV


ION PRODUCTION PROFILES, 10-18 MAY 1992 - ANOMALY / SOUTH
10 MAY, 2215 UT
12 MAY, 2233 UT
14 MAY, 0008 UT
16 MAY, 0014 UT
18 MAY, 2247 UT
ALTITUDE (KM)
100
90
80
70
60
50
40
30
20
1x10-2
1x10-1
1x100
1x101
1x102
1x103
1x104
Q (ion pairs/cm3-s)